Green nanotechnology in Nordic Construction: Eco-innovation strategies and Dynamics in Nordic Window Value Chains

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Green Nanotechnology in Nordic Construction

Eco-innovation Strategies and Dynamics in Nordic Window Value Chains

- The emergence of eco-innovation/the green market and the emergence of nanotechnology
- How does the emergence of nanotechnology affect the eco-innovation dynamics?
- Incentives, barriers and strategic response when facing possibly major changes in the reigning technological paradigms underlying the business.

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Abstract: This project analyzes Nordic trends in the development and industrial uptake of green nanotechnology in construction. The project applies an evolutionary economic perspective in analyzing the innovation dynamics and firm strategies in the window value chains in three Nordic countries, Denmark, Finland and Sweden. Hence the project investigates two pervasive parallel market trends: The emergence of the green market and the emergence of nanotechnology. The analysis investigates how a traditional economic sector such as the construction sector reacts to such major trends.

Conclusions are multiple, but among the most important are: Eco-innovation has become the perhaps most important driver for innovation in the construction sector. Search into eco-innovative business opportunities is intense among all companies along the three analyzed Nordic window chains. While we generally find a low uptake of nanotechnology in the construction sector in the Nordic countries we do find quite a high number of nanotech applications in the Nordic window chains. Eco-innovation is influencing strongly on the nanotech development. We see several examples of nano-enabled smart, multifunctional green solutions in the Nordic window chains already or about to having a commercial impact. Currently, it seems the greening of markets is beginning to affect the roles different companies play in the chain. We see a marked shift towards more systemic, smart eco-innovative solutions which fit well with nanotech opportunities. Overall, the recent greening of the market seems to be opening a window of opportunity for nanotechnology in the Nordic countries but the widespread discreet firm strategizing towards nanotechnology may reduce the exploitation of these.

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Executive Summary

This project analyzes Nordic trends in the development and application of green nanotechnology in construction. The project takes on an evolutionary economic perspective in analyzing the innovation dynamics and firm strategies in this area. Hence the project investigates two parallel market trends: The emergence of eco-innovation/the green market and the emergence of nanotechnology. The project seeks to analyze the interrelationship between these trends; i.e. does the rise of eco-innovation evoke the uptake of nanotechnology? And how does the emergence of nanotechnology affect the eco-innovation dynamics?

The analysis focuses on investigating how a traditional economic sector such as the construction sector reacts to these new market opportunities. This project hence emphasizes the multifaceted and dynamic nature of the economic process in accordance with evolutionary economic theory. It investigates the incentives and barriers firms experience and their strategic response when facing possibly major changes in the reigning technological paradigms underlying their business.

Within construction a case has been chosen looking into the window value chains in three Nordic countries, Denmark, Finland and Sweden. The analyses are partly in depth firm analysis with companies along the window chain, based on a mixture of interviews, secondary data and bibliometric analysis. Additionally, the analysis builds on national surveys, mapping the nano innovation activities and their relevance for construction in the three countries.

Conclusions are multiple, but among the most important are:

Eco-innovation has become one of the major drivers for innovation in the construction industry in all three analyzed Nordic window chains. While we generally find a low uptake of nanotechnology in the construction sector in the Nordic countries we do find quite a high number of nanotech applications in the Nordic window chains. Clearly, eco-innovation is influencing strongly on the nanotech development in the window chain. The need to outweigh possible nano-risk issues with societal (e.g. environmental) benefits in the nanotech area plays a role here. But it also seems that nanotechnology is offering novel green solutions to enduring problems in the construction sector. We see several examples of nano-enabled smart, multifunctional green solutions in the window chains. E.g. nanotechnology is already improving energy efficiency, energy control, self-cleaning glass, de-polluting materials/improving the indoor climate, environmentally friendly wood preservation and better light transmittance in glass of importance for the efficiency of solar energy and green houses. And we have seen a growing interest into green nanotech opportunities in e.g. anti-condensation materials, durable paints for wood and environmentally friendly metal corrosion treatment. Some of the nano-enabled products have been there for a surprisingly long time, 20-30 years (the nano-coatings applied by the big glass manufacturers), while many of the other applications are of a recent date. Our findings confirm a very slow nano-commercialization process despite the huge investments into nanoscience internationally the last 15-20 years.

The current policy regime has only partially stimulated eco-innovation in the construction sector. While regulation on energy efficiency towards buildings certainly has been a core innovation driver and let to major improvements in energy performance, it has also restricted innovation. The change towards more flexible policy measures in recent years in the construction and window area both internationally and nationally appears to be stimulating eco-innovation in new ways.

The situation in the window chain with a few very large technically advanced international glass manufacturers, many small mostly traditional glass processing and window manufacturers and a range of diverse project oriented construction companies create a difficult environment for new high tech materials ventures. Both incumbents, start-ups and the really big multinational companies have show to play important but different roles in the development and uptake of nanotechnology in the window chain.

Currently, it seems the greening of markets is affecting the economic organization considerably, and as yet stronger than nanotechnology is. The search for new green market opportunities is intense significantly affecting the competitive conditions and beginning to affect the roles of different companies in the chain. We see a marked shift towards more systemic, smart eco-innovative solutions which fit well with nanotech opportunities; i.e. eco-

innovation strategizing is shifting from the window to the building. A result is that improvements in energy performance of windows are so considerable that windows have changed from being part of the problem to being part of the solution for achieving energy efficient buildings.

Concerning business strategies there is though no explicit link between “green search” and “nano search” in the window chain to day. I.e. nanotechnology is not seen as a means to obtain eco-innovation as such. Generally many firms hold a discreet if not secretive strategy towards nanotechnology. There is much nanotech in the window chain that is little known which may backlash on the market development for nanotechnology.

The window case exemplifies waves in the economy where nanotech seems currently to be on the down-turn (though the picture is mixed here) and eco-innovation in the up-turn. The friction to eco-innovation on the market is hereby rapidly diminishing as “green” market institutions and practices are becoming established. The case analysis shows, however, several examples of remaining problems in market penetration of green products which illustrates a fundamental problem of many eco-innovations: It is often very complicated to estimate and communicate the environmental parameters.

The barriers to commercialization of nanotech are considerable in this early fluid stage of development where standards, capabilities and trust in the new technological field are lacking. Nanotech seems predominantly to be moving in the more high tech areas than in the direction of traditional sectors such as the construction sector. There is clearly a lot of unused nanotech potential in the construction sector if we compare our mapping surveys of potentialities undertaken and the actual activities in the case findings.

We have not been able to identify specific Nordic clusters or synergies as yet; the nano-activities in the window chains are quite different in the three countries. But more studies are needed in this little analyzed field.

Overall, the recent greening of the market seems to be opening a window of opportunity for nanotechnology in the Nordic countries but it is uncertain to what degree these opportunities will be exploited.

Content

Preface

This project is financed by the Nordic Innovation Center under an “eco-innovation” call. The project has been running in the period 2007 beginning 2010 but with some interruption underway.

We would like to thank all the companies and experts who have participated as respondents in this project. Apart from the official project participants also researcher Sergio Jofre and research assistant Maans Molin from the Technical University of Denmark have participated with early inputs in the analysis.

In accordance with the purpose of NIC to support exchange of ideas between academia and industry, the report is targeted at a wide audience and emphasis is placed more on empirical than theoretical findings.

1 Introduction

1.1 Background

The climate change agenda is currently reaching an unforeseeable international peek so far. With the massive international attention to the climate agenda, green competitiveness and eco-innovation is gaining unheard momentum as compared to only a few years ago. There is an increasing awareness that eco-innovation will be an important competitive factor in the future knowledge economy with still more affluent people sharing fewer resources (Andersen 2009; 2009b). A transition to carbon neutral energy supply and efficient conversion and use of energy is high on the political agenda and a fundamental basis for innovation. This is more than a fad. With an extended time horizon, we find that efficient use of energy of different forms has been an engine of human progress since the Neolithic revolution (Ponting 2007; Sanden 2008).

The effects of the strong climate agenda on the construction sector are considerable. Policy making at all levels around the globe have identified energy efficiency targets in construction as a matter of central importance for climate policy goals (Metz 2007). As buildings now make up approximately 40 percent of the energy consumption in well-developed energy-efficient countries like the Nordic ones and as much as 70 percent of the energy consumption in the booming enormous Chinese market, the market opportunities and need for action in the sector are enormous (Elvin 2007).

This project takes on an evolutionary economic perspective in analyzing the development and application of green nanotechnology in construction ("green nano-construction") at the firm level. Hence this project investigates two parallel market trends: The emergence of the green market and the emergence of nanotechnology. The analysis focuses on investigating how a traditional economic sector such as the construction sector reacts to these new market opportunities. The project seeks to analyze the interrelationship between these trends; i.e. does the rise of eco-innovation evoke the uptake of nanotechnology? And how does the emergence of nanotechnology affect the eco-innovation dynamics? This project hence emphasizes the multifaceted and dynamic nature of the economic process in accordance with evolutionary economic theory. It investigates the incentives and barriers firms experience and their strategic response when facing possibly major changes in the reigning technological paradigms underlying their business.

The construction sector is an example of a very traditional sector with a relatively low innovative capacity and productivity. But it is also a sector of great economic importance. Hence it is interesting to study such a sectors absorptive capacity towards nanotechnology as a science-based field. The sector differs from other industry sectors with regard to innovation patterns due to the project-based orientation of the production process as opposed to a process orientation (Taylor and Levitt 2005). This entails that firms enter into temporary coalitions and collaborate on constructing specific projects which limits the accumulation of knowledge. While at some level affected by this condition, many firms producing building components are process oriented and demonstrate a somewhat different innovation dynamics. In this study a case has been chosen looking into the industrial dynamics and strategies within the window value chains in three Nordic countries, Denmark, Finland and Sweden. The project focuses on windows because of the high relevance of environmental issues in this product area and the presence of interesting companies active in nanotechnology in the Nordic countries.

1.1.1 *The rise of eco-innovation*

The environmental agenda is increasingly moving from the more general regulatory oriented sustainable development agenda towards the market-oriented “eco-innovation” agenda. While the environment used to be considered a cost to business, the environment is increasingly seen as a business opportunity. None the least the recent strong global climate mitigation agenda has strengthened this shift. *Eco-innovations are here defined as innovations which are able to attract green rents on the market* (see also Andersen, 1999, 2002, 2007, 2009, 2010a, 2010b). They (appear to) reduce net environmental impacts while creating value on the market. Following this definition the eco-innovation concept is inherently linked to the greening of markets and green competitiveness. For this definition it is not decisive how green an innovation is but to what degree the environmental parameter has become a selection parameter on the market. Eco-innovation, then, is a measure of *the degree to which environmental issues are becoming integrated into the economic process (Andersen, 2009, 2010a, 2010b.*

The positive linking of economic and technical progress with environmental protection started in the 1970s and 1980 with scholars like Amory Lovins, Robert Ayres and Joseph Huber and has also been framed under the heading of ‘ecological modernisation’(Mol and Sonnenfeld 2000; Hawken et al. 2005). Only slowly did evolutionary economic research start to address environmental issues in the 1990s investigating into the innovation dynamics and green competitiveness of the greening of industry (See though e.g. Fussler and James 1996, Andersen, 1999, 2002, 2007, 2008, 2009, 20010a, 2010b, Andersen and Foxon, 2009, Fukasako 1999, WBCSD 2000, Rennings 2000, 2003, Hübner et al. 2000; Markusson, 2001, OECD 2005, Kemp 2000; Kemp and Andersen 2004; Foxon 2005, 2007, van den Bergh et al., 2006, 2007; Kemp and Paerson 2007; Reid and Miedzinski, 2008, Carrillo-Hermosilla et al. 2009, OECD 2009b). After the turn of the century these ideas started to make inroads into actual policymaking. One of the most significant of these is the EU European Environmental Technologies Action Plan (ETAP) of 2004 where new policy signals were sent in the simultaneous pursuit of environmental and competitiveness goals. ETAP created a renewed political interest at the European level in pursuing eco-innovations as a business opportunity, breaking with 60 years tradition of treating the environment as a burden to business (Kemp and Andersen, 2004). The new policy signals represented the rise of a new political paradigm characterized by novel synergies between environmental and innovation policy (Kemp and Andersen, 2004, Andersen 2007, 2009a, 2009b, Andersen and Foxon, 2009). With the recent rise of the global climate agenda a dramatic interest into eco-innovation policy has spread remarkably quickly around the globe. Not only Europe but countries such as e.g. Korea, Japan and China and lately the US are developing strategies for green growth in part as part of a green recovery plan to tackle the current world economic crisis (Andersen and Foxon, 2009).

The eco-innovation policy puts a much stronger emphasis on innovation dynamics than environmental policy hitherto has done. The perspective seeks to address the specific challenges different sectors and types of companies face when they are eco-innovative.

The construction sector has recently been identified as one out of three “lead markets” for eco-innovation as part of the EU ETAP policy making, where special efforts are made to promote coordinated policy action to enhance eco-innovation in the sector. This underlines the considerable current interest in promoting eco-innovation in the construction sector, mainly because of the huge energy saving potentials in the construction sector.

Energy efficiency is, together with renewable energy technologies and CO_2 reduction targets, one of the three core pillars of climate policy. (Andersen and Foxon, 2009, Andersen, 2009b). A range of new concrete policy initiatives and targets have emerged the last years none the least at the EU level, which is increasingly important for policy making in the Nordic countries. More concrete at the EU level the European Commission published its “Action Plan for Energy Efficiency” in 2006, followed by an EU energy policy. The current target is to reduce the EU’s CO2 emissions by 8 pct in 2010 and 20 per cent by 2020 relative to the 1990 base year. Buildings are identified as a priority. Underpinning these policies has been a series of EU Directives. The Energy Services Directive requires each Member State to draw up a National Energy Efficiency Action Plan by 2007. Lately, the new Energy Performance of Buildings Directive suggested in end 2009 aims to improve the overall energy efficiency of new and existing buildings, including the requirement to upgrade their Building Regulations for energy every five years. In this directive there is an important removal of the former 1000 m^2 thresholds meaning that small existing buildings finally are included in the energy efficiency demands. The requirement for all new buildings to be "nearly zero-energy" by the end of 2020 are core features, as well as the requirement for replacement elements, including windows, to meet cost-optimal standards are likely to influence eco-innovation in the construction sector and the glass and window production more specifically.

Most recently, the EU is considering developing an Eco-innovation Action Plan as a replacement of the current Environmental Technology Action Plan[1]. We may see this as an important consolidation of the emerging eco-innovation policy paradigm. The shift seems to form part of an overall tendency for innovation policy to become more horizontal and more engaged with societal problems (Andersen, 2009). There is also a stronger innovation oriented approach underway in the construction policy and nano policy area[2] (see also the final policy discussion in chapter 7).

1.1.2 The emergence of nanotechnology

Nanoscience and nanotechnology is the understanding and control of matter at a nanoscale, which is a billionth part of a meter (1 nm $=10^{-9}$ m) (US National Nano 2008). The significance of the nanoscale is that materials obtain new properties at this level. The size range of nanotechnology is normally limited to 100 nm down to the molecular level (approximately 0.2 nm) because this is where the properties, such as strength, electrical, chemical and optical properties, of a given material not only depend on chemical composition but also on size and form. This is mainly due to two reasons. First, nanomaterials have a relatively larger surface area. This can make materials more chemically reactive and affect their strength and electrical properties. Second, quantum effects can begin to dominate the behaviour particularly at the lower end of the nanoscale, which affects the optical, electrical and magnetic behaviour of materials.

Concerning nanoproduction methods two main routes can be distinguished (Royal Society 2004).

- *The Top-down approach* – entails the fabrication of nanoscale structures by applying specific machining and etching techniques (e.g. lithography, ultra precise surface figuring).
- *The Bottom-up approach* - also referred to as molecular nanotechnology, entails controlled assembly of atomic and molecular aggregates into larger systems (e.g. clusters, organic lattices, supra molecular structures and synthesised macromolecules).

Nanotechnology is currently not one technology but a technological conglomerate consisting of a very wide range of different techniques.

Technologies based on nanoscale effects are nothing new. Moreover, nanomaterials are not only manmade but also exist in nature. In fact, the biological world is a world of advanced nanomaterials. What has led to a nanotechnological breakthrough during the 1990's is the development and application of new sophisticated instruments to observe, measure and manipulate processes at the nanoscale level. Before these tools were available, research and development at the nanoscale was experimental trial and error (Royal Society 2004). An example of an old nanotechnology is heterogeneous catalysis for air purification which is a 30-40 year old well-established technology where the trial and error based initial development increasingly is being replaced and refined by a nanoscientific approach (Andersen and Rasmussen 2006).

At one end of the spectrum there are speculations that Nanotechnology may lay the foundation of completely new industries and even fundamentally change the relation between humans and technology (Joy 2000; Kurzweil 2005). At the other end, nanotechnology is essentially viewed as a new processes technology, enabling new functionalities of materials in the range of 1-100 nanometres, and can as such be particularly interesting for renewing

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[1] Non- paper: "Innovation for a Sustainable Future: From the Environmental Technologies Action Plan to the EU Eco-innovation Action Plan", presented at the Stakeholder Consultation Meeting on the EU Eco-innovation Action Plan, February 11, 2010.

[2] (EC, 2009a, 2009b), http://www.ectp.org/documentation/ECTP-SRA-2005_12_23.pdf

traditional materials industries such as construction. In any case, it is characterized as a general purpose technology meaning that it is expected to have a pervasive and transformative impact on the economy and lead to sustaining productivity increases and growth in a broad range of industries (Youtie et al. 2007). There is a global race to be in the lead of what many expect to be the next industrial revolution (Luther 2004). Despite the enormous and still rising research and development (R&D) investments in nanotechnology worldwide, nanotechnology is still at a very early stage of commercial development; much nanoscience is still pre-commercial (Wood, Geldart and Jones 2003; BMBF 2004; Lux Research 2004; Willems and van den Wildenberg 2004; BUILD-NOVA 2006; Aitken et al. 2006; Hullmann 2006).

Particularly at the beginning of the millennium there was much hype (extensive focus, debate and phantasizing) related to nanotechnology, with grand expectations of nanotechnology to restructure the world atom by atom. There are especially high expectations to nanotech's *eco-innovative* ('green', sustainable) potential. It is difficult to find a nanoreport or policy document where major environmental benefits are not a main or important claim (see e.g. NSET 2003; Nanoforum 2003; Royal Society 2004; Luther 2004; EC 2004; European Parliament Scientific Technology Options Assessment Committee 2007; Schmidt 2007; Elvin 2007).

The high environmental expectations to nanotechnology are related to some fundamental features of nanotechnology. Nanoforum (2004), for example, argues that self-assembly, i.e. the attempt to mimic nature's intrinsic way of building on the nanometre scale, molecule by molecule through self-organization, has eco-potentials because it is so extremely efficient (Nanoforum , 2004 p.39). Another Nanoforum report points to the energy efficiency of nanoparticles. The most relevant effect of nanoparticles for applications is the large amount of atoms exposed on the surface compared to the bulk material. The large surface area leads to a high reactivity, e.g. facilitating combustion processes, increasing absorption rates for light, or providing better catalysts which speeds up reactions and allows lower processing temperatures and use of less material (Nanoforum, 2003 p.89). Potentially the atom-by-atom construction of nanotechnology could allow the creation of ultra tailor-made highly reactive materials and products avoiding dangerous and messy by-products. An important feature of relevance for nanoconstruction is that nanotechnology allows the design of materials with multifunctional properties. A single nanomaterial can replace several traditional ones. E.g. nanocomposites may be strong, light, electrically conductive and fireproof. Nanocoatings may be self-cleaning, de-polluting and antimicrobial (Geiker and Andersen, 2008). By making technologies like solar cells, batteries and fuel cells more competitive, nanotechnology also have the potential to transform energy and transportation systems and thus reduce the environmental impact of society at large (Smalley 2005; Sanden 2008; Kushnir and Sandén 2010).[3] Regarding energy savings it has been observed that the production of many nanomaterials is fairly energy intensive on a gravimetric basis even with envisaged industrial production methods (Kushnir and Sanden 2008).

At the same time concerns regarding possible environmental and health risks related to nanotechnology are increasingly being addressed by scientists, companies and policy makers (Colvin 2002; Arnall 2003; Nanoforum 2004; Royal Society 2004; Aitken et al.2006; Friends of the Earth 2007; Mantovani et al. 2009; Knebel and Meili 2010). The uncertainty is still considerable but focuses mainly on the effects of free nanoparticles (Royal Society 2004).

However, overall as yet the knowledge on nanotechnology, and none the least green nanotechnology, is of a very general and superficial character. The hype associated with nanotechnology means that there is a tendency to focus on grand potentialities and spectacular risks rather than looking into real trends. There is therefore much uncertainty both as to the commercial development and the environmental opportunities and risks related to nanotechnology (Royal Society, 2004; Andersen and Rasmussen, 2006; Andersen and Geiker, 2008). More in-depth and critical studies are needed. There is particularly a knowledge gap on sector specific studies of the industrial up-take of nanotechnology. As it is now we know very little about which sectors are lead users in nanotechnology

[3] See also Jacobstein (2001), Reynolds (2001), Nanoforum (2003), Andersen and Rasmussen, (2006) and Elvin (2007) and Geiker and Andersen, (2008) for discussions on green nanotech opportunities.

and how nanotechnology enters into varies sectors. The current study seeks to contribute to this line of research in investigating the industrial uptake of nanotech in the construction sector.

1.1.3 Nanotech in construction

The construction sector was among the first to be identified as a promising application area for nanotechnology back in the beginning of the 1990s; but today we see that the fragmented and conservative construction industry is falling behind other sectors in applying nanotechnology (Gann 2002). Studies targeted at the role of nanotechnology in construction are very few and mostly quite recent. They are mainly either technical (Bartos et al., 2004; Zhu et al. 2004, Bartos 2005) or consist of consultancy reports presenting more a mapping of commercial nano-products than studies of trends, dynamics and impacts. An exception is (Andersen and Molin, 2007)

The enabling nature of nanotechnology implies that it can provide traditional construction materials with new functionalities including new eco-innovative solutions. The mentioned new reports identifies a wide range of commercially available products worldwide, illustrating that much is beginning to happen in this area (Nanoforum 2006, Scientifica, 2007; Elvin 2007; Freedonia, 2007; ObservatoryNano, 2009; Broekhuizen et al, 2009).

Table 1.1 gives an overview of nanoresearch and technology areas and their application in construction.

Interesting application areas relate to enhancing the functional properties of concrete, steel, wood and glass as the primary construction materials. Specifically, the embodiment of nanoparticles in the micro matrices or through coatings on the surface areas, of these materials can improve e.g. their strength, stress tolerance and durability leading to lighter, thinner and stronger materials. This, in turn, may have positive environmental impacts, e.g. through reduction of the use of wasteful raw-materials during the production, processing and transport of these raw materials. Further, energy usage becomes more efficient in buildings due to enhanced insulating and heat absorbing or controlling properties as well as energy efficient (LED) lighting systems.[4]

Table 1. 1 Nano in construction

	Properties	Products	Applications
Insulation	Efficient insulation due to extremely high surface-to-volume ratio, reduced toxicity and dependence on non-renewable resources. 30% more efficient than conventional materials.	Aerogel Thin-film insulation Insulating coatings	In structural and non-structural assembling
Coatings	Insulating nanoparticles can be applied to substrates using chemical vapour deposition, dip, meniscus, spray, and plasma coating to create a layer bound to the base material.	Self-cleaning coatings Anti-stain coatings Depolluting surfaces Scratch-resistant coatings Anti-fogging and anti-icing coatings Antimicrobial coatings UV Protection Anti-corrosion coatings Moisture resistance	Windows and structural surfaces
Adhesives	Material with adhesive surfaces, replacing traditional chemical adhesives. Eliminates residues and increases adhesive force.		structural and non-structural assembling and sealing
Lighting	Increases lighting power while reduces energy and resource consumption.	Light-emitting diodes (LEDs) Organic light-emitting diodes (OLEDs) Quantum dot lighting	indoor and outdoor environments
Solar energy	Increases efficiency on energy generation while reduces cost and material intensity.	Silicon solar enhancement Thin-film solar nanotechnologies Emerging solar nanotechnologies	non-structural components
Energy storage	Improved efficiency for conventional rechargeable batteries, new super capacitors, advances in thermovoltaics for turning waste heat into electricity, improved materials for storing hydrogen, and more efficient hydrocarbon based fuel cells.		building and indoor systems
Air purification	Filter particles, eliminate undesirable odours, and removal of airborne harmful element.		Indoor system
Water purification	Water decontamination, purification and desalinization, and providing improved detection of water-borne harmful substances.		Indoor system
Structural materials	Improving resistance, flexibility, strength and life span while reducing deterioration rate, volume and weight.	Concrete Steel Wood New structural materials	structures
Non-structural materials	Increasing strength and durability while reducing heat losses.	Glass Plastics and polymers Drywall Roofing	window systems

Source: Elvin 2007

The early studies into nano-enabled construction are indicating, however, that the industrial uptake of nanotechnology is still limited and that the majority of construction companies, universities and other knowledge institutions have little insight and experience with nanotechnology (Gann, 2002; Bartos et al. 2004; Zhu et al. 2004, Bartos 2005; Luther and Zweck, 2006; Nanoforum 2006, Andersen and Molin, 2007,Scientifica, 2007; Elvin 2007; Geiker and Andersen, 2008; Observa-

[4] See for example Elvin (2007), Andersen and Molin, (2007), Geiker and Andersen, (2008) and Smith and Granqvist (2010) for discussions on the eco-innovative potential of nanotechnology in construction.

toryNano, 2009; Broekhuizen et al, 2009). When talking about nano-construction we are therefore still dealing much with potentialities (Andersen and Molin, 2007; Green Technology Forum, 2007).

A Danish analysis shows a generally weak demand for nanotechnology in the construction sector:

> 'The overall picture of the demand for, knowledge of, and views on nanotechnology in the construction sector is that knowledge and expertise are currently too fragmented to allow for a substantial uptake, diffusion and development of nanotechnological solutions in the construction industry. At present, only very vague ideas of the possible benefits can be identified among key agents of change such as architects, consulting engineers and facility managers. Furthermore the demand side will be reluctant about introducing nano-technological materials until convincing documentation about functionalities and long-term effects is produced. A need for documentation of the consequences for health and safety is evident.' (Andersen and Molin, 2007, p.32)

According to the recent reports, barriers for the wider development of nano-enabled construction are considerable and lie mainly in four areas: a) the lack of knowledge of nanotech opportunities in the construction sector b) reluctance of the sector towards (radical) innovation, c) the high costs of some, but not all, nanotechnologies, and d) public concern about nanorisks (Elvin 2007, Scientifica 2007).[5]

The recent consultancy reports are, however, largely based on web-searches and nano-product inventories based on databases largely dominated by small nano-dedicated companies or the very large multinational companies. This means that these studies are biased towards the role of upstart companies and multinational companies for nanotech evolution. We know currently very little about the role of medium sized incumbent companies for nanotech development, this also goes for the construction sector, and even more specifically, companies in the window chain. Existing analysis say nothing about the industrial dynamics involved in the uptake of nanotech in construction. With the exception of Gann's early work in 2002, and a small Danish study from 2007 (Andersen and Molin 2007) there are no nano-innovation studies in the construction area, nor any studies analyzing green nano-innovation.

There have been no studies specifically on nanotech in windows, but there are some examples of nano-enabled products in the glass and window area in these general reports as also shown in Table 1. We know, however, currently nothing about the general development and application of nanotechnology in the window chain.

1.2 Project objectives

The overall aim of the project is to investigate innovation dynamics and firm strategies in green nano-enabled construction in the Nordic countries.

Additionally, the project has the following objectives:

- To identify Nordic opportunities for commercialization and possibly Nordic synergies within green nanotech related to construction.
- To suggest policies for strengthening Nordic innovative capacity in the area of green nanotechnology in construction
- Additionally, the project seeks to disseminate its findings and further info on green nano-construction towards the Nordic countries via cooperation with nano-active Nordic organisations (NaNet in Denmark, NanoØresund in Sweden and Spinverse in Finland) and via its webpage www.greennanocon.org.

In accordance with the purpose of NIC to support exchange of ideas between academia and industry, the report is directed to a wide audience and emphasis is placed more on empirical than theoretical findings.

[5] While risks issues are dealt with very little in the Elvin report (2007) which focuses narrowly on identifying green nano opportunities in construction, it is dealt with more thoroughly in the Broekhuizen report (2009).

1.3 Theoretical points of departure

Although this report is not very theoretical, it should be made clear that the work builds on a tradition broadly captured by the term Evolutionary economics. Rather than concentrating on markets in quilibrium, the focus here is on economics as a process dominated by innovation where uncertainty is high, information is lacking and in flux (Nelson and Winther, 1982). More specifically the report draws on three sub-areas within evolutionary economic theory:

We make use of the innovation cycle literature to gain an understanding of the different stages characterizing technology evolution and the role different types of companies and other actors as well as institutional change play in these stages (see e.g. Abernathy and Utterback, 1975; Tushman and Anderson, 1986; Grübler 1996,). At the micro level the life cycle metaphor can be applied to individual technologies (see e.g. chapter 6 on smart windows). At this level we are interested in the sequence of events from research finding to market entry created by a dynamic interplay between general trends and internal feedback. At the technology level focus is onthe gestation times and development patterns as technologies evolve and go through early fluid materialisation stages to formation and consolidation. At this level we are interested in analyzing the development patterns and current stage in nanotechnology evolution and the role respectively upstart and incumbent companies play in commercializing nanotechnology. More specifically we are investigating how nanotechnology enters the window chain.

Similarly,and as yet little recognized, the emergence and development of a green market can be viewed from an innovation cycle perspective, undergoing stages of formation and consolidation as environmental parameters gradually become integrated into the economic process (Andersen, 2009). We may perceive the greening of the economy as a specific historical phase evolving in the global economy, though with considerable regional and sectoral differences (Andersen, 2009). Currently, however, our understanding about sectoral patterns in eco-innovative behaviour is limited. The question addressed here is how companies along the window chain strategize to turn environmental parameters into a competitive advantage in an increasingly greening market (Andersen, 2009).

We draw on various innovation systems frameworks for the understanding of the co-evolution of organisations, science, technology and institutions in specific settings (see e.g. Freeman, 1987; Freeman, 1995; Lundvall, 1992 (ed.), 1999, 2005; Nelson, 1993; Metcalf, 1995; Edquist, (ed.) 1997, OECD 2005; Freeman and Loucã, 2001, European Commission 2003, 2006; Fagerberg et al. 2008; Bergek et al. 2008). The research question emerging from this literature is the role of surrounding institutions, including policymaking for the innovation process. This line of thinking can be used to understand the specific innovations conditions characterizing certain countries or regions such as the Nordic ones or certain technology areas, such as nanotechnology. In chapter 2 we discuss the Nordic innovation conditions shortly.

We are inspired by the "evolutionary capabilities" perspective (Teece, 1986, 1996, Langlois 2001, 2008) in analyzing changes in the way learning and production is organized across firms under consideration of their transaction costs. The research question here is what strategies different types of companies apply to pull in the necessary complementary assets to succeed with their innovations. Related to this Maine and Garnsey (2006) suggest that the commercialisation of advanced materials technology such as nanotechnology meets specific challenges due to its generic and radical character and its upstream position in value chains. The matching process between technological capabilities and demands in a specific market is particularly difficult for technologies that are based on new scientific knowledge and can be applied in many different applications.

1.4 Report layout

Chapter 2 provides a brief outline of innovation and nano-innovation conditions in general in the three Nordic countries as well as within nano-enabled construction. The latter is mainly based on the surveys, or mappings, of nano-innovation activities and their relevance to construction that were conducted for the three countries (see the appendix 1-3 for the results of the surveys). Chapter 3 briefly discusses the conditions for glass and window production more generally as well as in the Nordic countries.

The main part of the study is captured in three case national studies reported in Chapter 4-6. The case studies address the empirical field of green nano-innovation in Nordic window value chains from different angles. They are not constructed as country comparisons but demonstrate complementary aspects of the phenomenon. Chapter 4 focuses on window manufacturing in Denmark and demonstrates a somewhat surprising multitude of nano-activities as a response to the environmental challenge. Chapter 5 focuses on opportunities and barriers in the industrial uptake of nano-coatings in the Finnish glass-processing industry and on the position of new dedicated nanotechnology companies in the glass-processing and construction value chains. Chapter 6 focuses on a Swedish university spin off and trace the long struggle to get an innovation from lab to market. All of these three case studies are primarily based on semi-structured interviews but they are backed up with bibliometric data and secondary data as well as web sites and supported by the national mapping surveys carried out as part of this project (see further below).

Finally, Chapter 7 brings the most important analytical conclusions as well as a policy discussion.

2 Trends in Nordic nano-enabled construction

This section shortly highlights some characteristics of innovation in general and nano-innovation in the Nordic countries based on statistics and existing data as well as new bibliometric studies. Succeedingly, we shortly discuss status in nano-enabled construction in the three Nordic countries

2.1 The Nordic innovation environment

The Nordic countries are interesting to compare because they have fairly similar economies. They are typically highlighted as models of well-fare economies which are able to align a high standard of living, with high social care but also a high score on innovative capacity.

Table 2.1 depicts the innovation performance of the three Nordic countries in focus in this report, Denmark, Sweden and Finland, in terms of four types of socio-economic capital indexes and one innovation index. Compared to the overage EU 27 performance, the three countries exhibit remarkable good results in all dimensions, see Table 2.1 below.

Table 2.1. Socio-economic capitals and innovation indexes in Nordic Countries

	Performance Indexes			
Variables	**EU 25**	**Den-mark**	**Sweden**	**Finland**
Cultural capital and consumer behaviour*	100	116	109	111
Interest in science and technology	100	109	125	96
Optimism towards science	100	101	99	97
Attitude towards risk of new technologies	100	155	136	117
Attitude towards future	100	76	70	93
Attitude towards environment	100	147	112	158
Attitude towards other cultures	100	115	117	112
Customer responsiveness	100	107	102	104
Human capital*	100	153	126	93
Human resources in science & technology	100	127	123	126
Nationality of HRST	100	63	81	23
Higher education rate	100	145	127	109
Human resources in knowledge-intensive services	100	119	121	104
Mobility	100	190	135	109

Participation in life-long learning	100	317	198	77
Availability of qualified personnel	100	112	97	104
Social Capital*	100	134	134	209
Cooperation with competitors	100	113	82	261
Cooperation with academy	100	122	155	296
Customer as a source of information	100	137	138	204
Trust	100	156	156	137
Corruption	100	144	140	147
Organisational capital & entrepreneurship*	100	122	115	113
Initiative at work	100	103	108	100
Empowerment	100	133	140	124
Relation between employers & employees	100	130	109	99
Risk aversion/entrepreneurship	100	11	121	130
SMEs organisational innovation	100	150	115	123
Organisational rigidity	100	106	100	102
Innovation Index**	(0.45)	0.61	0.73	0.64
Rank (among 37 countries)	17	5	1	3

Best performance Sources: * Europe Innova 2008, ** Europ. Innovation Scoreboard 2007

Despite some differences in innovation patterns and socio-economic capitals in terms of national innovation performance, all these three Nordic countries are situated at the top of global innovators; Sweden being first, Finland third and Denmark fifth. These results suggest that there may be a high absorptive capacity towards new market opportunities such as eco-innovation and nano-innovation in the Nordic region. The disparities with regards to the four types of socio-economic capital mean though that the response among the countries may present different patterns and results.

Particularly interesting for our study are three aspects (highlighted in grey): 1) the very high attention to environmental issues (Finland and Denmark very high, Sweden still high but somewhat lower), which indicates a pro eco-innovative behaviour, 2) A very similar a medium score on optimism towards science, which indicates a positive but careful attitude towards a new science-based technology as nanotechnology, and 3) a shared very high attention to risks of technologies, particularly high in Denmark and Sweden, which indicates a more hesitant response to a new technology as nanotechnology that are associated with some risk issues.

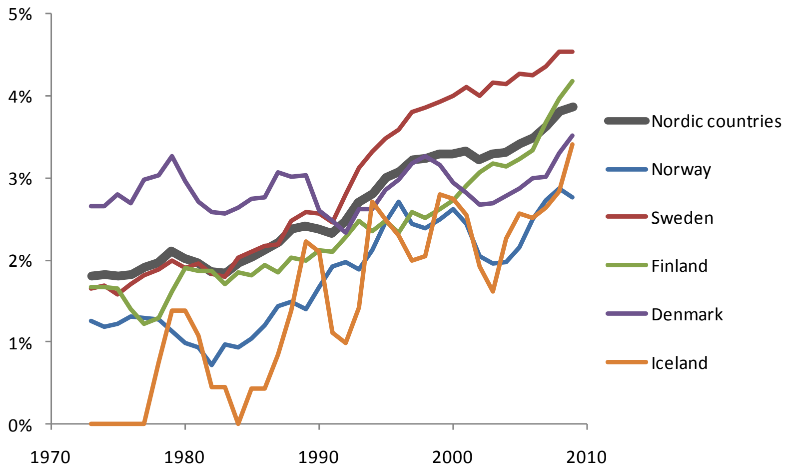
2.2 Nanotech trends in the Nordic countries

The precedent observation is confirmed by our findings of the comparative analysis of nanotechnology uptake within the three countries. In general, Denmark, Finland and Sweden present a notable development in nanoscience and nanotechnologies while their uptake patterns differs, notably in terms of organizational arrangements, industrial involvement and research and development focus. Although the R&D intensity of Nordic countries in the field is online with the EU average – and therefore lower than in US and Japan current leaders in the area – the scientific production of these countries is considerable (Cordis, 2005). In terms of nanotechnology EPO patents, Sweden shares 1% of total applications, Denmark 0,5%, and Finland 0,3% (OECD, 2007). Nordic scientific production in the area is also relevant, with Sweden having a 2.05% share of the overall production, Finland 0.73%, and Denmark 0.69% (Kostoff et al, 2007). In terms of most cited articles, the positions among the countries remain the same.

To capture the development of nanoscience over time a bibliometric index was constructed that captures the relative share of advanced materials science in the total flow of publications. Materials science developments may be used as a proxy for developments in nanotechnology with highest relevance for the construction sector. The search excludes nanoscientific developments in biochemistry and medicine but includes publications on what could be viewed as nanoscience but that is published in journals that currently are classified under different headings, such as thin-film technology.

Figure 2.1 below shows that with the possible exception of Denmark which has a more uniform development, materials science has dramatically increased its share of academic publications in the Nordic countries over the last three decades.

Figure 2.1. **The rising share of materials science in the Nordic countries**



Source: Materials science is approximated by two subject areas (Materials science, multidisciplinary OR Physics, condensed matter) in Science Citation Index and weighted against all publications from the respective countries. The graphs represent three-year moving averages.

In Denmark nanotechnology has become an important research and development area particularly the last 5-10 years. Four new nanoscience centres have been established in this period connected to all the main Danish universities. Also a high-technology national network, NaNet, has been formed but this was closed down in 2009, as it was concluded that the well-established nano science centres were capable of managing on their own by now. There is no national nano strategy but the high Technology Foundation provides funding targeted at the nanotech, biotech and ICT area. Quantifiable data on the industrial development in Denmark are so far poor, but one study shows that there are approximately 58 companies involved on research and development collaborations with academy and an estimated 14 nanotech firms (VINNOVA, 2008), see also (Risoe 2005, Andersen and Rasmussen, 2006, Andersen and Molin 2007 for other analyses).

Based on figures from 2006 in Finland there are about 500-600 researchers in universities, research institutes and companies working in the field of nanotechnology. Research and firm communities are emerging in close vicinity to the main technical universities in Finland. The biggest concentration of research and firm activity is found in the Helsinki region where the University of Helsinki and Helsinki University of Technology play an important role, along with the Technical Research Centre of Finland (VTT). Both Tekes and the Finnish Funding Agency for Technology and Innovation (Tekes) have supported nanotechnology indirectly (e.g. through programs in the areas of new materials, health-care and electronics) and through the FinNano nanotechnology-dedicated programs since 2005. While absolute levels of R&D investments are low in international comparison Finland is emerging as a significant funder on a per capita basis with levels comparable to those in France, Germany and the UK (Palmberg and Nikulainen, 2008)

Dahlöf and Wihed (2010) estimate that 600 MSEK was invested in research related to nanotechnology in Sweden 2008. The research is conducted by approximately 700 researchers at 20 universities and university colleges. In 2007, a similar survey found nano-activities at 15 of these institutions (Perez and Sandgren 2007). The most recent study found 117 Swedish companies active in nanotechnology as compared to 85 in the 2007 study. Out of the 117, 45 are classified as dedicated nanotechnology companies that base their enterprise on nanotechnology and 35 of these are university spin-offs. During 2009, a first Swedish national strategy for nanotechnology was prepared under the lead of Vinnova (Borälv et al. 2010). The strategy does not recommend any special nano-policy. However, it stress increased focus on coordination of Swedish nanoactivities nationally and internationally, integration of risk assessment in the innovation process, active linking of nanotechnology capabilities to global challenges, application areas and industrial sectors, mobility of staff and public participation. For a historical account of nanotechnology in Sweden see Fogelberg and Sandén (2008).

2.3 Trends in nano-enabled construction in the Nordic countries

This section shortly seeks to describe emerging trends in the industrial uptake of nanotechnology in the Nordic countries, i.e. to highlight what direction nanotechnology seems to be taking at the current early stage of development. Special emphasis is placed on discussing the uptake in the construction sector.

In *Denmark* the mapping of Danish nanoscience and innovation activities undertaken in 2007 shows generally limited activities in the field of construction. A previous nearly similar mapping but focusing on green rather than construction issues was undertaken in 2005 (Andersen and Rasmussen 2006). The mapping shows which nanoscientists and companies are active in different emerging nanotechnological areas, the commercial stage of development as well as the Danish international position in the field.[6] The current section also builds on an earlier study on nano-enabled construction in Denmark (Andersen and Molin 2007) as well as a study of green nano innovation in Denmark (Andersen and Rasmussen, 2006) and a Danish nano foresight (Risoe, 2005).

The overall conclusion is that Danish nanoscience as well as technology is oriented primarily towards the direction of medico, energy production and catalysis (catalytic cleaning). Also, commercial development is in many cases very early if not pre-commercial. Given the early stage of development the data on industrial uptake and the ability clearly to define nano-active companies is quite poor. A conclusion is that much Danish nano science has a limited industrial orientation or even lacking application orientation, which illustrates the very fundamental nature of some nano science (see also Andersen and Rasmussen, 2006, Andersen, 2006, Andersen and Molin, 2007).

Concerning construction, Danish nanoscientists and nano-active companies are currently only in a limited way involved in or oriented towards the construction sector. The two mappings carried out in respectively 2005 and 2007 seem to show a rising activity in the construction area in this period, but this may mainly be due to the fact that the second mapping specifically inquired into construction matters. A strict quantitative comparison is not possible due to data insecurity[7]. The analysis has to some degree showed a disinterest in the low-tech construction sector amongst the Danish nano scientists; e.g. some reluctance to participate in our mapping exercise and the workshop on nano-enabled construction carried out as part of this project. An earlier study into nano-enabled construction in Denmark shows a lacking attention to and insight into the needs of the construction sector by nano scientists as well as companies (see also chapter 1) (Andersen and Molin, 2007).[8]

The current mapping shows that a great number of nano science or technology areas are estimated to have potentials for construction application but it has not taken place so far. Most of the Danish nano-active companies in construction are in the field of building materials and components. Their numbers are not very substantial yet

[6] The mapping is based on estimations by core nano scientists and companies via an electronic and email based survey, in part interviews. The most part of it was carried out in 2007 at the beginning of this project. The mapping has only been partially updated since then. The mapping is too extensive to be included in the current report.

[7] The response rate to the first mapping, based on a similar methodology,– the first quantitative analysis of nanotech in Denmark- was much greater than the second which unfortunately was partial- only two out of the four nano science centers participated seriously. This makes a quantitative comparison very difficult and the data should be treated carefully.

[8] This may possibly also illustrate the fact that it is a new exercise for the nanoscientists to consider the application opportunities of a specific sector, because such an approach has not been carried out in Denmark before.

though. Many are in an early stage where they may be only just entering R&D activity in the field; strategies are not yet decided or declared. An exception is the nano-concrete area, which is the most mature nano-enabled area within construction in Denmark. For this study, the most interesting finding is that the window company VELUX is among the companies most widely represented in the mapping, showing an interest into a great number of different nanotech themes. The window company Velfac is also represented a couple of times. VELUX and Velfac are among the core case firms in the Danish case in chapter 4.

The supply side is mainlymade up of nano-dedicated companies most of which are not yet oriented towards construction, but with potential interests in this area, such as Nanon and Haldor Topsøe. There are more recently also a few nano-dedicated upstart companies orienting themselves towards the construction sector, such as Superwood, Accoat and Photocat, who too form part of the Danish case.

In *Finland* a recent company survey from 2008 identified 200 companies with nanotechnology activities, compared with 64 companies in 2006. The majority of these companies operate in the chemicals and materials, healthcare and ICT industries. This survey only identifies 6 companies in the construction industry, but many of the smaller and nanotechnology-dedicated companies are developing applications which could also be used in this industry[9]. Despite increasing company activity and patenting the number of Finnish nanotechnology products is still low and commercial breakthroughs are still limited as is the case in most other countries as well. A key issue in the commercialisation of nanotechnology in Finland is the degree to which this emerging technology finds use in traditional industries in which established companies already have developed world-renowned business niches (good examples include the metals and engineering and forest-based industries); many of these industries also face pressures to renew themselves to cope with increasing global competition . Previous studies suggest that the technological specialisation of Finnish nanotechnology matches the technological specialisation of the country as a whole, thereby pointing to the potential widespread applicability of nanotechnology in Finland. Further, innovation development times may be shorter in traditional industries – such as the construction industry – in which nanotechnology mainly add new functionalities to already existing materials and products in already existing markets (Palmberg and Nikulainen, 2008).

In *Sweden* the nano innovation system has a clear focus. Two thirds, or 78, of the Swedish companies with identified nano-activities belonged to one of the two sectors bioscience and electronics (Dahlöf and Wihed 2010). Only four firms were classified as construction sector companies. However, the mapping of nano-activities undertaken during this project at Swedish universities displays a broad range of research with potential application in the construction sector[10]. This is not surprising with regards to the longer term time trend of increasing research in materials science in Sweden (Figure 2.1). In the mapping, projects at different levels of maturity are listed. One can conclude that many projects that were identified in this survey are now in a phase of early commercialization and prototyping. For many, it will still take many years until they break through.[11] As noted in Section 2.2, the Swedish nanotechnology strategy points out the importance of finding ways to strengthen networks between academics developing nanotechnology and firms in different industries with knowledge on applications and markets (Borälv et al. 2010). This is very much in line with our findings. Currently there appears to be some distance between many of the nanotechnology researchers in our survey and firms in the construction industry. Applications in construction are clearly not in focus for most nanoscientists and dedicated nanotechnology companies.

In the mapping, it can also be noted that research on nanorisks has recently started. An early inclusion of risk assessment in the innovation process would probably benefit uptake and diffusion in the construction sector. This aspect is highlighted in the Swedish nanotechnology strategy (Borälv et al. 2010).

[9] http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/NANO/fi/etusivu.html

[10] The mapping is not included in this report as it is too extensive.

[11] When evaluating commercialisation of research results we need to keep in mind the long time lags between invention and innovation. In Chapter 6 a Swedish case is described where research in thin-film physics was taken from first experiments at the university to a product ready for implementation in the construction sector. This far the process has taken almost three decades.

3 Innovation in the window chain

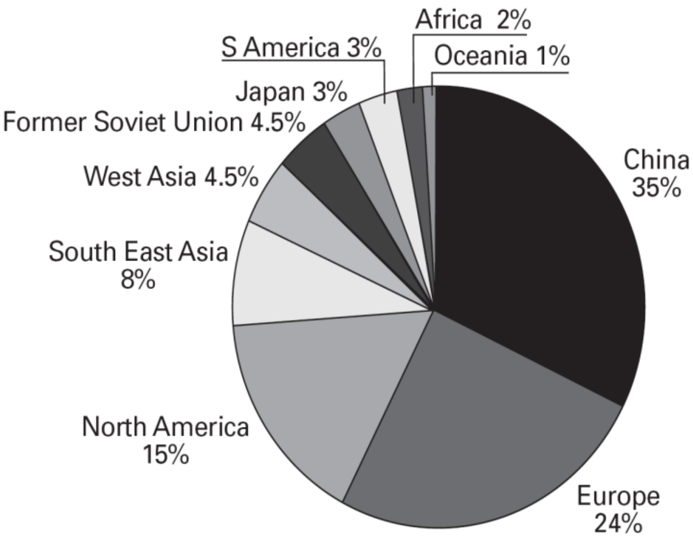
This section shortly seeks to identify some characteristics of innovation in the window chain. Most emphasis is placed on glass manufacture which has undergone major structural change greatly influencing the innovation dynamics of the window chain. Also, the evolving big multinational glass producers are key nano-innovators and therefore of considerable importance to this study. The window manufacture has not undergone the same structural change, and is only briefly touched upon.

3.1 Window and glass production[12]

While window production is relatively small scale and dominated by many small companies, glass production is highly industrialized and dominated by few very large multinational companies. Modern glass production is continuous, large scale mass production and highly capital intensive. A modern float plant is typically costing around $90 million to $190 million. The economics of continuous production require a high capacity utilisation rate – typically above 70% – before a plant becomes profitable. Energy and raw material costs are significant. Glass is relatively heavy, making distribution costs significant. Typically transport costs represent around 10% to 15% of total costs, making it uneconomic for float glass to travel long distances by land. Typically, 200 km is the norm, and 600 km is the economic limit for most products. The global market for flat glass in 2005 was approximately 41 million tonnes. This is dominated by Europe, China and North America, which together account for around three-quarters of demand. The significance of China as a market for glass has been increasing rapidly since the early 1990s. In the early 1990s China accounted for about one fifth of world glass demand, but now accounts for over one third. The economic crisis is likely to greatly affect the demand for flat glass negatively in the coming years.

Figure 3.1 The distribution of the global flat glass markets

[12] Mainly bassed on Pilkington 2009 and http://www.glassforeurope.com.



Source: http://www.glassforeurope.com/theindustry/FactsAndFigures/

The construction sector is the main customer. Between 80% and 85% of the total output is used for construction products, and 15% to 20% for automotive and transport applications. In buildings glass is not only used in windows but increasingly also in building façades as an alternative to other building materials, such as brick, wood or polycarbonate.

Today's glass products represent highly advanced products in contrast to the simple glass of the past. With technological innovation glass has come to meet a growing range of functionalities apart from light and panorama, such as safety (breakage resistance), security (resistance to burglary), fire resistance, noise reduction, thermal insulation, solar control (to control heating), anti-reflective, self-cleaning, anti-scratching and decoration. These high-value products are made from processing the basic float glass by laminating, toughening and coating, as well as assembling the glass into insulating glass units (double or triple glazing).

Today's glass and window products for the construction sector are subject to numerous strict quality and performance assurance mechanisms such as those formalised under EU law and the European Committee for Standardisation (CEN).

3.2 Eco-innovation in glass

By far the dominating environmental issue in glass and window production has been energy efficiency. By controlling the ability of glass to capture natural heat and light, there is a huge potential for reducing the carbon output associated with heating and ventilation. Over the past 25 years, in mature markets such as Europe, Japan and North America, the growing need for energy efficiency has encouraged a switch from single glazing to insulated glazing units (also known as double-glazing or more seldom triple glazing) (Pilkington 2009). Growing concerns about climate change, fuel prices and energy security are, in a rising number of markets around the globe, driving legislative requirements for the use of energy-saving glass technologies in buildings, such as making insulated glazing unit's mandatory (the case in many parts of Europe) and requiring the use of energy-efficient coated-glass products. This quest for energy efficiency has boosted demand for low-emissivity ("low-E") glass, solar-control glass (for reduced ventilation), and photovoltaic and solar thermal energy.

Refurbishment of existing buildings accounts for around 95% of glass consumption worldwide, driven largely by the need for increased energy efficiency, where newer technologies in windows and glass façades provide significant improvements over older products. The replacement of single-glazed units by double-glazed (or more seldom triple-glazed) windows, have roughly doubled the amount of glass used. Hence the glass and window industries have early had a strategic interest into energy efficiency issues. The outdoor climate plays a role, making low-energy glass most wanted in colder climates and solar control glass demanded in the warmer regions, leading to significant reductions in ventilation needs. The specific regional distribution of these energy-efficient glasses and windows are not documented, so we do not know where the lead markets are. The policy focus has been very much on the energy performance of the pane (the glass) where as attention to the energy performance of the window frame and the overall functioning of the window have come much later.

There are naturally also other environmental concerns related to window products, none the least the reduction of wastes which presents a huge problem in the construction sector because of the sheer amounts, but there are also concerns about the handling of hazardous materials, as we shall hear more about in chapter 4,5 and 6 on the Nordic cases.

With the new strengthened international policy emphasis on energy efficiency related to the hot climate agenda, such as e.g. the mentioned EU requirement for all new buildings to be “nearly zero-energy” by the end of 2020, eco-innovation strategizing is likely to gain increased momentum in the window chain in the coming years.

3.3 Industrial structure[13]

This section gives a short overview of the competitive conditions and structural changes in glass and window production. While the emphasis is on the Nordic countries it is necessary to take an international outlook as particularly glass manufacturing is heavily globalized and dominated by multinational companies. Major technological innovations have taken place in the glass industry which have had decisive effects on the structure and concentration of the industry and the wider window chain. To understand the current structure and functioning of the Nordic window markets we need to take a short look at the evolution of the glass and window industry. Succeeding, we will focus specifically on the Nordic conditions.

Glass production has experienced several radical technological innovations as the production changed from handcraft into industrial production during the 20th century. Accordingly, the period has been characterized by competing technological trajectories and the gradual emergence of a dominating design around float glass production. These changes have influenced heavily on the evolution of the industry structure. The core actors in this process were central European and American companies, the winners being among the dominating global companies of today. Glass and window production has traditionally had a strong national orientation particularly in smaller countries such as the Nordic ones. The question is how the peripheral Nordic markets have been part of these international developments over time and how the competitive conditions are today. Generally speaking the main technological innovations have been adopted relatively late in the Nordic countries.

Two companies, the British Pilkington and French Saint Gobain dominated early the European flat glass industry and are today among the world leading multinational companies in this field. Modern large scale float glass production was invented by Pilkington in 1959 which gave the firm a decisive competitive advantage. The technology was licensed and quickly spread globally. Preceding this radical innovation in the glass production process there were two competing sub-industries, respectively the “sheet glass” and the continuous “plate glass” industries which co-existed as late as the 1970s. Float glass production was invented out of the plate glass industry. The capital large scale plate glass industry was much more concentrated than the more localized sheet glass production.

Float glass production emerged from and overtook plate glass production very quickly. The large plate glass producers were also large sheet glass producers but float glass production only moved into sheet glass production in 1968-70. Pilkington closed down its last plate glass production in 1967. Already by the end of the 1970s sheet glass producers had nearly disappeared globally. Meanwhile float glass production accelerated the globalization of

[13] Unless otherwise stated the section is mainly based on Uusitalo (1997, 2004) who has studied the evolution of the flat glass industry in the Nordic countries from 1900-1990 and Pilkington, 2009.

the plate glass industry and float glass production became the global dominating design for flat glass production. Two other big global players, the US PPG and the Japanese Asahi had proceeded with modernization of the sheet glass production very late and only converted their last European sheet plants to float glass production as late as the early 1980s.

These technological process innovations have given rise to productivity gains but also advances in product innovations such as thinner and cheaper glass. Already by the 1930s more advanced product innovations emerged, the first being safety glass (laminated and toughened) aimed for the highly innovative automotive sector. Safety glass was central for the development of plate glass and float glass production. Multiglass units for better heat and sound insulation were developed in the US and Germany in the 1930s aimed both at the construction and automotive sectors. Prefabricated insulating glass units were preferred to two or three individual panes of glass in a window.

Today global flat glass production is dominated by few very large multinational companies. The most important ones, also on the European and Nordic markets are NSG (Pilkington), Saint Gobain Glass, Asahi (AGC), Guardian Industries. In 2004 it is estimated that those four companies alone held a combined share of at least 80% of the flat glass market in Europe.[14]

Below in table 3.1 the core figures of the leading MNC in flat glass production are given with an emphasis on European conditions. Only the most relevant data are given as these companies are too complex to cover fully.

Table 3.1 Core figures on the leading MNC in flat glass production

Companies Parent and *European glass subsidiary*	**Localization** Headquarter Main markets	**Product area**	**Size and scope**
Nippon Sheet Glass Co (NSG)	Japan 43% of sales in Europe, 27 % in Japan & 16% in North America	Flat glass (90%) Specialty glass (ICT, glass fibre)	The world's largest producer of flat glass with 51 full-or part-owned float glass plants, manufacturing operations in 29 countries on five continents and sales in 130 countries. 32.500 employees
Pilkington (NSG)	UK Europe/world	Flat glass manufacture	Europe only: 13 float glass plants, two coating plants,4 laminating plants, 2 rolled glass plants, glass processing and wholesaling through 49 units in 10 countries
Asahi Glass Co (AGC)	Japan	Flat glass & construction materials, industrial materials, biotechnology, chemicals, electronics, optics and telecommunication	The second largest flat glass producer.

[14] Source: http://europa.eu/rapid/pressReleasesAction.do?reference=IP/07/1781, IP/07/1781 Brussels, 28 November 2007.

AGC Glass Europe	Belgium World	Flat glass manufacture	Europe: 18 float glass plants, 7 automotive glass plants and some 100 processing units. 14.500 employees
Saint-Gobain	France World	Construction Products, Flat Glass, Containers/ Packaging, High-performance Materials, Building Distribution	The third largest flat glass producer, among top hundred industrial groups worldwide. 209.180 employees
Saint-Gobain Glass	Europe , America, Asia rising	Flat glass manufacture magnetron coated glass	30 float lines worldwide including 13 joint ventures, and 13 coating facilities. 300 units for processing and distribution in Europe
Guardian Industries *Europe:* *Luxguard*	US EU: Luxembourg, World	Glass, Auto Parts, Fiberglass & Building Products	The fourth largest flat glass producer. No 50 on Forbes list of largest companies. World's largest glass coating plant in Luxembourg. 19.000 employees
Sisecam *Europe:* *Trakya Cam*	TurkeyEast European, Balkan, Middle East & North African markets	Flat glass production	top eight flat glass company and top four company in Europe 2.886 employees.

Source: Company webpages and Wikipedia accessed during 2009, and the report "Pilkington and the flat glass industry 2009". Ranking of world top companies by production volume.

From the table the strong dominance of these giant companies in the flat glass markets globally and noticeably in Europe is apparent. There is some regional specialization but most companies compete on most global markets. All these big players have a varied product portfolio in flat glass production directed at both the construction and automotive sector, the Guardian though with limited automotive activities. The NSG Group is the most focused glass company, just less than 90 per cent is concerned with flat glass; Asahi lies considerably lower at 50 per cent while Saint-Gobain's flat glass focus is the lowest of all the majors at just 13 per cent (Pilkington, 2009). Several of the parent companies have extensive activities in other parts of the construction sector, and relevant for nanotech development, also in materials and chemicals. They are to varying degrees involved in glass processing too and all extensively in glass distribution.

While these big companies all have strong R&D efforts there is currently little documentation on the scope of their nanoscience and -technology activities. Very little if anything is apparent from their webpages and own information material and no analysis have been made on the subject. The company PPG (no. six in size), however, markets it-self strongly as a nano company hence displaying a very different nano marketing strategy from the rest of the big players[15]. Much indicates however that it is only a difference in marketing strategy and not innovation strategy. Danish experts in the area state that basically all modern flat glass coatings are based on nanotechnology and that nanoscience has dominated glass coatings the last 30 years, long before the rise of the nanotechnology buzz word (see the Danish case in chapter 4). We will hear more particularly on Pilkington operations in the Danish and Finnish case studies.

[15] PPG: "Nanotechnology Enabled Materials for Energy Conservation", presentation at EPA conference September 25, 2007 on "Pollution Prevention through Nanotechnology"

In 2007 the EU commission imposed fines on the four leading glass producers on the European market, Asahi, Guardian, Pilkington and Saint-Gobain, totalling € 486.9 million. The cartel coordinated the price settings for flat glass for use in the construction sector during 2004-2005 until the EU competition commission intervened.[16] While cooperation between these companies since then is restricted they still have a shared lobby platform *Glass for Europe*, the trade association for Europe's manufacturers of flat glass. Pilkington, Saint Gobain Glass Solutions, AGC and Şişecam are the only members and Guardian Industries is associated.

Flat glass is today used in a variety of end products, the main two user groups being construction/architectural (windows and façades) and automotive (windscreens and windows for automobiles). It is also used in much smaller quantities for many other applications like appliances and electronics, solar energy equipment, interior fittings and decoration and furniture. Some of the big flat glass producers also produce other types of (none-flat) glass such as packaging.

The window industry has not undergone the same amount of major innovations and concentration as the glass industry. Window production is still characterized by small scale production, a relatively low R&D with many small carpenter firms still playing an important role. However, bigger and more R&D oriented companies are emerging.

3.4 Developments in the Nordic countries

In the Nordic countries the hand blown sheet glass manufacturing disappeared in the 1920s and 1930s as drawn sheet glass production took over.[17] Only sheet glass production took place in the Nordic countries as these markets were too small to sustain the large plate glass plants. The Nordic producers were small but sufficiently big to serve their local markets. In 1960 there were seven independent Nordic sheet glass manufacturers; Three in Finland, two in Sweden, and one in both Norway and Denmark. All these companies invested heavily in new sheet glass technology as late as the 1960s and early 70s. Float glass was early imported to the Nordic markets after its invention in 1959 exploiting the good trading relationships with the UK.

In the 1970s Pilkington and Saint Gobain became interested in the Nordic flat glass markets. In 1974 and in the following years Pilkington made massive marketing in the Nordic countries and invested in whole sale companies to form a basis for its first Nordic float glass plant which started in 1976 in Sweden. Saint Gobain also started production merging a Swedish, Norwegian and Danish producer. A war on prices broke out and other Nordic producers closed down or sold their production to either Pilkington or Saint Gobain during the 1970s and 1980s. Pilkington and the Finnish government built a float glass production in the mid 1980s. Today the only Nordic float glass manufacture is the Pilkington owned plant in Sweden, as the Finnish Pilkington plant just has been closed down. There is, though, considerable glass processing going on in the Nordic countries. Pilkington and Saint Gobain still dominate the Nordic markets through their national offices or subsidiaries.

The window industry has been well represented in the Nordic countries that have a strong tradition for wood based production, and still wood remains the absolute dominating raw material in Nordic window frame production. The production is to a large degree directed at the home markets.

, [16] Source: http://europa.eu/rapid/pressReleasesAction.do?reference=IP/07/1781, IP/07/1781 Brussels, 28 November 2007.

[17] Unless other wise stated the section is mainly based on Uusitalo (1997, 2004) who has studied the evolution of the flat glass industry in the Nordic countries from 1900-1990, as well as Pilkington, 2009.

4 Pervasive innovation: The case of green nanotech in the Danish window chain

This chapter investigates the strategies and innovation activities of core actors in the Danish window chain towards green nanotech. The analysis has sought to identify which actors are active in nano-related innovation in the Danish window chain and inquire into their strategies and innovation processes.

It appears, that quite many actors have shown to be active in nano-related innovation, but to varies degrees and in very different ways. The Danish analysis takes its focal point amongst the core Danish window producers, the dominating and well-established VKR group and the smaller company PRO TEC. Hence the Danish case seeks to cover the response to and uptake of green nanotechnology in incumbent firms, but also to some degree to shed light on the activities and strategies of some of the other core nano-active companies; mainly the leading big glass supplier Pilkington DK and the start-ups Sunarc (glass), Superwood (wood impregnation) and Photocat (nano-catalytic materials). The case then is mainly producer oriented. Inputs are also provided from experts in the field, i.e. Danish scientists, advisors and NGOs on windows, energy efficiency and nano coatings.

The main data input are from interviews and the mentioned mapping in chapter 2, but the case also builds on secondary data, websites and statistics as well as related earlier studies by the author in the nanotech, green nanotech and nano-construction area (see Andersen and Rasmussen 2006, Andersen and Molin 2007, Andersen 2006, Geiker and Andersen 2009, Andersen And Geiker, 2009).

The chapter is structured as follows: The first section brings a short overview of the core actors in the Danish window innovation system. The second section focuses on the main market and policy demands for nanotech and eco-innovation as experienced in the Danish glass and window sectors. The next core sections look into the green nanotech activities and strategies by different actors in the window chain. Finally, a concluding section discusses trends in strategies and industrial dynamics in the Danish window chain.

4.1 The Danish innovation system for windows

As other innovation systems, the Danish innovation system for windows is becoming increasingly integrated in the globalizing economy. With the Danish innovation system we consider the core actors (companies, knowledge institutions, industrial associations, NGOs ect.) and institutions (policies, infrastructure, cultures..) operating from or influencing on the Danish market for windows and glass.

In Denmark there are a range of small window producers but only relatively few big ones. The by far biggest Danish window producers all belong to the same group, the *VKR Group,* which forms the focus of this case analysis. While most of the small Danish window producers are little innovative there are a few examples of more high-tech innovators. Relevant for nanotech development is the up-start company PRO TEC as we shall return to.

There is no float glass production left in Denmark so the Danish glass industry deals with glass processing or whole sale. The company members of the Danish Glass Association are made up of 29 companies Danish, German or Polish. [18]The biggest ones are Pilkington Denmark, Scan Glass (Danish subsidiary of Saint-Gobain),

[18] www.glasindustrien.org

SEMCO (German), Swan Glass (Danish) and Glaseksperten, Hjørring. The niche company Sunarc uses nanotechnology to produce specialized glass products.

The Danish window producers draw on a range of other material and product suppliers, the most important ones being among wood, metal and plastic material suppliers as well as firms dealing with varies surface treatments (paints, coatings and impregnation technologies). The Danish nano active suppliers we shall return to are both established producers such as Dyrup (paint) and Accoat and (coatings), and small nanodedicated start-ups, such as Photocat (nanomaterials and coatings) and Superwood (impregnation), a company recently bought up by VKR.

The Danish window customers are made up of few relatively big Danish construction contractors and a wide group of architect companies as well as public purchasers. The home market for windows remain the most important, export making up approximately 26% of the manufacturer's total revenue. There are a little less than 300 companies in the Danish window sector, most of these relatively small, representing 6000 employees and a turnover of 6 billion DKK.[19]

Below table 4.1 brings an overview of the main companies in the Danish window innovation system of relevance for nanotechnology development. I.e. these are the companies that we shall return to in the rest of the chapter; some are dealt with in more detail (in bold), others only superficiously. The companies are grouped according to their position in the value chain.

Table 4.1 Core nano active companies in the Danish window chain

Companies	**Affiliation and country**	**Product area**	**Age**
Fiberline Composites	DK	Composite materials for buildings and windmills	Year 1979
Dyrop	DK	Paint	Year 1928
Accoat	DK	Coatings	Year 1969
Superwood	VKR Group (DK)	Wood (nano) preservation	Year 2002
Photocat	DK	Nano photocatalytic materials for glass and floors	Year 2009
ScanGlass	DK under Saint-Gobain Glass (Fr)	Glass processing, wholesale,	Year 1935, *(Saint-Gobain 1976)*
Pilkington Denmark	DK under Pilkington NSG Group	glass wholesale and minor processing,	Year 1978
Sunarc Technology	DK	(nano-) sheet glass for solar collectors, PV-modules, greenhouses	Year 2000
VELUX	VKR Group (DK)	Roof windows and skylights	Year 1941
Dovista, made up of **Velfac** and Rationel	VKR Group (DK)	Vertical windows and doors	Dovista 2004 Velfac 1961 Rationel 1954
PRO TEC Vinduer	DK	Vertical windows	Year 1993

[19] www. Vinduesindustrien.dk accessed November 2009

Source: Based on company webpages and interviews. Data in italics refer to the mother organization. Company names in bold are those mostly analyzed in this case.

Hence the analysis covers most but not all the identified nano-active companies in the Danish window chain.

Firms deal with nanotechnology in very different ways which is so far little analyzed. Here a six category taxonomy is suggested which sheds light on important differences in firm nanostrategizing:

Some of the firms are *nanodedicated*, (Sunarc, Superwood, Photocat) where nanotechnology forms a fundamental part of their capabilities and innovative activities. Others are *nanospecialized* where nanotechnology forms a serious but not necessarily central part of their R&D. The main multinational glass producers are among the leading nanotech developers within the construction area, but they also have many other capabilities. The core window company VELUX and the surface treatment suppliers Dyrops and Accoat are *nano-active* in a more partial way where nano R&D play some but not a very central role for their innovative activities. Their nano innovation is to a large degree centered on applying and integrating nanotechnology developed by others into their current activities. Some firms are merely *nano-interested*, with no nano-development activities but inquiries and some level of research into nanotech opportunities (here Velfac/Dovista though moving into the nano-active category). Other firms are *nano-users* with no R&D in nanotech themselves but applying nano enabled products (e.g. many construction companies and architects). Finally some are *nano-shadow* companies such as Fiberline. Nanoscientific insights are important as nanoscale properties matter for their underlying technology base (in this case plastic composite materials) and there is quite a lot of development into nano-enhanced composite materials; but the company does currently not or only limited seek to develop or apply nanotechnology. The nanotech capabilities typically reside with their suppliers (the chemical or plastics industry). These companies are potentially nano-dedicated companies.

Quite many companies fall within this latter for nanotechnology distinct group which illustrates the special history of nanotechnology. Much nanotechnology existed long before nanoscience emerged following the development of the new advanced nano-microscopes, but as a trial and error rather than science based technology[20]. Hence many technologies or materials have attained the nano prefix ex post their development, and many, who potentially could, have never obtained it. In some cases these areas are now being nurtured and renewed by nanoscience development (for example in the for nanotechnology old and in Denmark very well-established catalysis area), in others such as part of composite research, this is only partially taking place yet so far though developments are rapid (see also Andersen 2006, Andersen and Rasmussen 2006, Andersen and Molin 2007). The glass manufacture area resembles the catalysis area in being a traditional nano-enhanced sector since the rise of advanced coating technologies.

Generally, nanotechnology is playing a surprisingly if not important then rising role for Danish glass and window innovation, particularly considering how little this is known. There are varies development projects and quite some new applications going on and some of these are likely to influence the Danish and international markets considerably in a few years. Interestingly in the Danish case is the VELUX company which displays a for a window company unusual high interest into nanotechnology. While some of the nanotech products have difficulties in penetrating the markets none the least due to a risk aversion, their green potentials are very important drivers as we shall illustrate further.

A range of none market organizations and institutions have influenced on the development and market penetration of glass and windows in Denmark in important ways. Many of these have directly played a role in R&D activities or, more often, influenced on the policy, certification and standardization formation in this area as highlighted in section 4.3 on policy and market trends. The most important current ones are shortly introduced below.

The key Danish knowledge institutions in the window area are the following. At the Technical University of Denmark, the Department of Building and Energy, noticeable professor Svendsen's group, has played an im-

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portant role in research into the energy efficiency of windows and was a key actor in a major research project “Project window” (see later). SBi (the State Building Institute) plays an important role as advisors and publishers on (“building recommendations”) also in the window area, including on energy efficiency issues related to windows. The Raadvad center advices on and works to preserve old construction techniques and has been a very active player in the Danish debate on energy efficient window techniques. The Danish Technical Institute, the Department for Building and Energy, both works with R&D and as advisors of companies. The latter have been administrators of the Danish standards in the area in a close cooperation with “Byggecentrum” and the Danish glass and window industrial associations.

Also green NGOs have been important in the energy efficiency debate in Denmark. Noticeably “Energitjenesten”, who mediates information on energy efficiency to the public supported by public funding, including on window issues.

The key industry associations are: “VinduesIndustrien” (The Association of Danish Window Manufacturers) is an association for manufacturers of windows and external doors. The association also has technical committees and four material groups. “Glasindustrien” (the Glass industry in Denmark) is the industry association for European producers, processors and distributors of glass on the Danish market. It represents thus the main players in glass processing in Denmark, including over 95% of the large Danish production of insulating glass. The association develops and publishes certification schemes and standards as well as instructions and data sheets for architectural glass, including e.g. the energy labeling scheme for insulating glass. The certification schemes are administered by the Danish Technological Institute. The Glazier Guild in Denmark also plays a role for the distribution of glass in Denmark.

4.2 The core Danish glass and window companies

In the following the core features of the most important window and glass producers will be shortly introduced to outline how the Danish markets for glass and window works: The VKR Holding, Pilkington Denmark and ScanGlass.

The Danish *VKR Holding* is by far the dominating window Group in Denmark. While the companies belonging to VKR Holding traditionally have centered its activities on window production, they have currently activities in five business areas: 1) Roof windows and skylights, 2) vertical windows, 3) thermal solar energy, 4) decoration and sun screening and 5) natural ventilation.[21]

VKR Holding A/S is a limited company wholly owned by foundations and family. The Group has overall approximately 16,000 employees and operates in more than 40 countries. Three main companies make up the window section of the VKR Group. The dominating *VELUX* entity specializes in producing and selling roof windows and skylights where they hold an internationally well known brand. In addition, VELUX offers decoration and sun screening, roller shutters, installation products, products for remote control and thermal solar panels for installation in roofs. The VKR group’s 17.3 billion DKR revenue comes mainly from VELUX which holds 60% of its employees. VELUX has manufacturing companies in 10 countries and sales companies in just under 40 countries.

The Dovista Group within VKR specializes in developing and marketing vertical windows and doors. They employ 4,000 people and hold ten brands represented in seven countries. The two entities *Velfac* and *Rationel* are the main Danish producers of vertical windows and glass facades. Dovista handles the R&D for Velfac and Rationel, while VELUX has its own R&D department.

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[21] Source: http://www.vkr-holding.com/ ,www.VELUX.com, http://www.dovista.com/, "http://en.wikipedia.org/wiki/VELUX", modified on 21 October 2009

Pilkington Denmark (NSG Group) was established in 1978, when Pilkington bought up two Danish glass wholesalers. The intention was to secure the sales on the Danish market of the float glass originating from the new Pilkington float glass plant in Sweden (in Halmstad from 1976). Pilkington Denmark has seven sales departments and one insulating glass plant. The head of technical customer service, C.A. Lorentzen served also as a leading lobbyist on building glass and policy matters, but since November 2009 this function has been closed down because of the financial crisis and moved to Sweden[22]. Building glass makes up half their sales.

The glass sold in Denmark comes as mentioned from the Swedish float glass plant and is mainly sold to insulation glass producers, including their own. More insulating glass is today imported from abroad than produced in Denmark, increasingly Eastern Europe. Pilkington owns the largest insulating glass plant in North Europe which lies in Poland and supplies most of the Nordic markets. Transport costs are considerably because glass is heavy so the glass is primarily bought fairly locally. Pilkington estimates that within 5-10 years developments in the fuel/CO2 costs and labour costs will mean that the insulating glass plant in Denmark will be more profitable and the main supplier to the Nordic markets. All products for buildings need to be CE-labelled which restrict import from many developing countries. But Pilkington/NSG has rising production activities in an increasing number of countries.

Saint-Gobain Group operates since 1976 through the Danish subsidiary Scan Glass, which used to be the main Danish sheet glass producer. Today the SCAN GLASS Group is the largest glass processing company in Denmark with three producing units. Additionally there are 5 departments that serve the local craftsmen and smaller industries. It employs approximately 300 employees and consists of 8 offices in Denmark. SCAN GLASS primarily supplies insulating glass for the window frame manufactures aimed for the construction sector but it also delivers advanced glass products for glazing and interior market. The company draws on the advanced product development in the large Saint-Gobain Group. Saint-Gobain's network of glass processing and -distribution businesses in the construction sector in Europe employ more than 13.500 people across Europe and have 300 divisions. Denmark is well-represented, also compared to the other Nordic countries, see map below.

Figure 4.1. Saint Gobain’s glas processing and distribution businesses

Source: www. Saint-Gobain.com

4.3 Danish policy and market demands for nanotech and eco-innovation in windows

1.C.A.Lorenzen is now glass-advisor in Glasfakta Aps. and the Northern European lobbying function has been moved to the Swedish Pilkington company.

Market and environmental policy trends are closely interrelated on the glass and window market and hence these are treated together in this section.[23]

In Denmark there are around 3.5 million buildings with approximately 60 million square feet of window area. Heat loss through these windows alone represents today seven per cent of Denmark's total energy consumption (SBi 2003). There are therefore considerable energy savings to obtain by making existing and new windows more energy efficient and energy efficiency has long been an important policy issue influencing on Danish window development in multiple ways.

The Danish building regulations have played a key role in setting very direct framework conditions for the use of windows in Denmark. While energy efficiency has been an important Danish policy issue since the mid 1970s the effect of the policy measures on eco-innovation in the glass and window sectors is, however, not clear-cut. The regulation is being criticized for not fostering energy efficient solutions properly. Oxenvad, Energitjenesten, and Lorentzen (Pilkington Denmark) state that Danish manufacturers only develop or uptake new technologies as a respond to regulation[24]. Oxenvad states: “The Danish window producers have been focused on timing their innovations to the policy process but they are reactive in their innovative activities. They are proactive when lobbying; they have seen where the market – that is policy – is moving and they are controlling it to a large degree. So the strong policy dependency has restricted innovation in this area.” [25] According to Oxenvad, energy efficiency has not been a major innovation driver among the Danish window companies[26]. The Danish companies in the construction chain he sees as having been quick in picking up energy efficient (“low E” glass but slow in making triple layer windows or energy efficient frames. “There was an expectation that the market could not bear the extra costs of the energy efficient solutions. Competition was on lowering maintenance rather than energy efficiency.” The increasing energy efficiency meant that many wood based windows had increasingly problems with condensation and rot. The focus on maintenance meant that first plastic frames were imported from Germany in the early 1980s (which never became a success); in the mid 1980s wood-alum window production began in Denmark. These quickly spread to most producers and the market share for these products continues to grow, despite problems with thermal bridges in these. These windows were successfully marketed for their aesthetics and low maintenance (“you don’t need to paint your windows any more”).

Oxenvad judges that the consumer has little insights into windows and their many properties. As people only need to buy windows once or twice in their life there is no need to built competencies in this area. Even the professional customers such as municipalities, construction companies and architects often lack insights on the many functional dimensions of modern windows. Lorentzen from Pilkington often need to serve as advisor during the design phase. The big companies are doing marketing courses directed at these professional users.

Particularly the last 2-3 years competition has increased on the Danish glass and window market due to the internet. Do-it yourself windows, none the least low energy windows have become easily accessible via the internet. This has greatly increased the competition on price but also allowed the users to get more in-depth information on the product functionalities. For the glaziers the internet sales have become a serious threat and many have closed down already.

The Danish window market is 50 pct. renovation in Denmark and 50 pct. new built or export. 54 pct. of the Danish windows are made up of 2 layer insulating glazing.[27] The use of triple layer glass is very low, almost exclusively used in green demo houses or spectacular buildings, whereas this is a standard in Sweden, Finland and

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[23] The section is based on interviews with Danish window producers in the VKR Group as well as Pilkington Denmark, and two core experts on energy efficiency (a scientist and a NGO), a government official as well as policy material, reports and webpages of the window and glass associations.

[24] According to interview with Oxenvad, Energitjemesten, Jan13 2009 and Carl A. Lorentzen, Pilkington, 16 January 2009.

[25] According to interview with Christian Oxenvad, Energitjenesten 13 January 2009.

[26] According to interview with Christian Oxenvad, Energitjenesten 13 January 2009

[27] Interview with Poul Thorsen, director of ”Glasindustrien” (The Danish Glass Association) 28/10 2009.

Norway, possible because these have somewhat colder climates. It has not been possible to get further data on the market penetration of different advanced glass and window products on the Danish market.

Particularly the energy performance of the window frame has been neglected according to Svend Svendsen, Professor of Building Energy Engineering at the Technical University of Denmark: "The insulating performance of glass has radically improved in recent years. The goal now is to match this with better window frames and sills, thereby upgrading the energy balance of the window as a whole."[28]

The policy dependence of the window producers seems, though, to be changing quite substantially in recent years with the dramatic rise of the climate agenda. New more proactive market oriented eco-innovation strategies are formed and a stronger innovation orientation seems to be developing.

4.4 The framework conditions for the Danish window market

This section seeks shortly to discuss the core policy initiatives affecting window energy efficiency. A very wide range of initiatives have been in place in what is quite a complicated policy area and here only the main elements will be touched upon. Some of these are aimed directly at windows, others more generally at buildings, often distinguishing between existing buildings and new builds.

The conditions for Danish window production as part of the building sector have changed considerably during the last 30 years and environmental policy has played a major role. The normative policy initiatives may be divided into six periods:

1) 1948-1961: A period dominated by government loans and normative demands requiring two layer windows in all new builds. Before this there were no policy initiatives.
2) 1961-1978: The first building regulation requiring U-values of 2,9 for vertical and 3,0 for roof windows.
3) 1979: The third Building regulative following up on the oil crisis in 1974. The energy consumption of a house was regulated by specifying the maximum area of windows (15 pct.) that could be placed in a house as windows were considered heat losers compared to the rest of the climate shield. A greater window/door area is allowed if further insulation is carried out elsewhere in the building. U-values for new builds were set at 2,9.
4) 1995-2005: The building regulative required 2,0 U-value in new builds. The areal demand was extended to 22 pct. and included now doors as well. A greater window/door area is allowed if further insulation is carried out elsewhere in the building.

EU: Directive 2002/91/EC on the Energy Performance of Buildings

Danish Action plan for the future energy saving effort, 2005

EU: Action Plan for Energy Efficiency, 2006

5) 2006-2009 "Energy frame considerations" are replacing U-values in the building regulative for all buildings - for the first time existing buildings are included as well. Demands on the energy performance of a building based on an energy labelling for buildings is introduced. No specific requirements for windows, except for extensions: U-value 1,5 for vertical windows and 2,0 for roof windows.

EU: 2009 Climate policy goals of 20 pct. energy efficiency gain by 2020. The building sector should cut 300t of CO2 per year by 2020.

EU: 2009. Launch of upcoming new directive On the Energy Performance of Buildings.

Danish Strategy for the Reduction of energy use in Buildings, 2009.

[28] Svend Svendsen Professor of Building Energy Engineering at the Technical University of Denmark, quoted www.fiberline.com

6) 2010-: New law and building regulative under way (expected agreed upon in spring 2010.) Core features are: The nergy balance (Eref) is used to estimate the energy efficiency of windows, see table 4.2. The energy frames limiting how much energy new buildings must use are tightened by 25 percent in 2010 and further 25 pct. In 2015. Further increases will take place in 2018 for public buildings and others in 2020. There will be component requirements on energy efficient renovations, also minor ones.

As is clear from the above outline U-value concerns on glass have been the core driving force for Danish window innovations until quite recently. Concerning new builds Denmark was the first country to implement the EU-directive of 2002 via the changes in the building regulative in 2005. This implied not only a tightening of energy requirements but the introduction of the important “energy frame/energy balance” perspective. This entails that the entire window energy performance is considered (and not only the pane) and both the heat gain produced as sun shines in through windows and the heat loss as energy radiates away from the windows of the house. Hereby incentives are created to find components which reduce a buildings energy needs. Overall, the legislation for window has changed from exclusively regulating the U-value of the glass (the heat loss), to regulate the entire window’s energy balance. Hereby the perspective is shifting towards a more complete view on energy efficiency in windows and buildings.

Also other policy measures, noticeable various information initiatives on energy efficiency have taken place in the more recent years, including a window campaign 2004-2006 for energy efficient windows.

Table 4.2 Calculations on energy efficiency in windows

U-value: *also* called the overall heat transfer coefficient, describes how well a building element conducts heat. It measures the rate of heat transfer through a building element over a given area, under standardized conditions. The smaller the U-value the better.
g-value: measures the solar energy transmittance through windows. (called "solar heat gain coefficient (SHGC)" in the US).
Eref: also called the “direction-oriented energy balance”, describes the overall energy saving potential of the window. The formula is:
E = Ikorr · Fs · gw - G · Uw [kWh/m2], where: I = direction oriented solar radiation during the heating season, adjusted for vertical facade window. Fs = shadow factor (for a standard Danish house DS418: 0.7) gw = window g-value [dimensionless] G = more hours in the heating season (Denmark: 90.36) [kkh] Uw = window U-value [W/m2K] gw = gg x Ff gg = glass g-value Ff = window glass share

Source: www.eref.dk/, http://www.velfac.dk/Global/Eref_eller_U-vaerdi#Begreber

The oil crisis in 1974 created the first serious interest into energy efficiency of windows and buildings which affected the Danish window innovation activities significantly. As a result windows with one layer of glass were to a high degree replaced by double-glazed windows; i.e. windows with small pane areas were replaced by windows with one large double-glazed pane. This raised discussion as to the changed architectural expression (to the worse) of a large number of old buildings and was an important element for the creation of the first Danish association of window manufacturers in 1977.[29]

The window area limitation of the late 70s[h] and 80s created incentives for developing narrower window frames but also to houses with few windows and poor lighting quality. Low energy houses became synonymous with

[29] www.vinduesindustrien.dk

minimal windows, and thus appeared more as a threat than a business opportunity to the glass and window industry.

The first large (DKK 35 mio.) Danish research project on windows, "Project window", which ran 1999- 2001 has influenced on the policymaking as well as debate on windows significantly. It had a strong focus on energy efficiency issues. The core knowledge institutions, (BYG DTU and SBi, DTI) were the main actors but industry (glass and window manufacturers) participated as well. Central in project window was Svend Svendsen's group at DTU BYG who suggested to replace the U-value with the mentioned "energy balance" calculation for the entire window later used in the energy frame policy making. Another core emphasis was on analysis of the pros and cons technically and economically of low energy glass, at that time little disseminated on the Danish market, contra standard insulating windows. Project Window also infused a public debate around 2001 on the pros and cons energy wise on replacing old windows with new more energy-efficient ones (SBi 2003).

An outcome of project window established a few years later was a new consumer energy label directed at windows based on an energy balance calculation, internationally quite rare at this time rating the windows from A to F. When the labels eventually were made for windows it became apparent that many Danish windows only scored an E or D.[30] According to interviews with Oxenvad, Energitjenesten, Svendsen, DTU and Lorentzen (Pilkington Denmark), there were quite serious problems with many of the Danish windows these years, not only in their energy performance but also problems with condensation and mold. Particularly Velfac windows were heavily criticized in this period; a television programme in 2008 and subsequent media storm set focus on the problems and affected the market.

The strong focus on energy efficiency promoted the use of large scale glass facades particular in office buildings. Some of these encountered succeeding major problems with overheating and bad indoor climate.

The project window thus facilitated important analysis and discussions. Unfortunately, as the project finished there was a policy regime shift in Denmark (from left to right in 2001), which led to a dramatic drop in policy interest into environmental issues, also in the window area. The results from project window were therefore little followed up.[31] 2002-5 were years of little activity and funding opportunities in the environmental area in Denmark.

In recent years EU regulation has overtaken the primary regulatory role towards windows. With the beginning rise of a strong international climate agenda around 2006-2008 Danish policy interest into environmental affairs and energy efficiency grew again; now also among rightwing politicians. Currently, infused by Denmark heading the UN COP15 meeting end 2009, Denmark is seeking to take on an international leading role in climate policy issues, meaning that renewable energy technologies but also energy efficiency is high on the political agenda. Most recently they are planning an innovation program for the promotion of energy-plus buildings. Also a recent "green recovery" renovation fund of DKK 1,5 billion has contributed to boosting the market for window replacements in 2009, but it is not expected to be continued.

Following the disappointing UN COP15 climate meeting in December 2009, the future of the international and Danish climate policy agenda is somewhat uncertain, albeit climate issues still appears a very important topic in the coming years.

According to Svendsen, DTU, the new upcoming tightening energy requirements while positive in many ways do not sufficiently support the newest product innovations in windows.[32] Svendsen wrote a report last year for the Danish Building and Economics Agency on policy recommendations in the window area but these have only partially been taken into consideration. It will still be possible to select less energy efficient windows and he fears the weak regulation may jeopardize the emerging market for the new composite windows. According to the respon-

[30] According to Oxenvad, Energitjenesten, January 9 2009

[31] According to Oxenvad, Energitjenesten, January 9 2009

[32] Interview with Svend Svendsen, DTU, January 5 2010.

sible government official in the Enterprise and Construction Authority many of the new window types Svendsen points to in his report are few and still prototypes or at an early stage of development where the durability and adequacy for existing buildings are little known, for example for small pane windows.[33] They see new builds as the place for taking product innovation forward in the window area. The agency expects the window policy issues to change considerable the coming years towards 2015, e.g. putting more emphasis on the location on windows and increased "moisture resistance" in the window frame putting increasing demands for minimum temperature in the window frame.

4.5 Eco-innovation strategies among the Danish VKR window producers[34]

The Danish window producers in VKR Holding have traditionally competed primarily on price, quality and design parameters and the ability to make customized solutions. Increasingly eco-innovation has become an important parameter. The VKR Holding Group as well as the companies within it, all has a strong environmental strategy with certified procedures and specified targets. E.g. the VELUX climate strategy is two-fold:

"We will save energy as a company by rationalizing our operation

We will supply products that can help others to save energy – in other words, contribute to Sustainable Living." [35]

VELUX has committed them to cutting the Group's 2007 global CO_2 emissions by 20% by 2012 and 50% by 2020.[36]

The recent growth in climate change mitigation has placed a much stronger demand for energy efficient windows which represent new market opportunities for the Danish window producers; but it has also represented a threat to the window industry because of the trend towards reducing the amount of windows in the low-energy/-passive energy/plus energy houses.

The Danish VKR window companies analyzed have reacted to these new competitive conditions in reformulating their strategies putting increasing emphasis on energy efficiency issues via the concept of the "active house". The "active house" concept represents an alternative way to deal with the same issues that the reigning low energy concept of "passive house" does, in emphasizing not only energy efficiency issues but also the well being of the people living in the house. In developing these strategies by these companies the window is increasingly seen as an integrated part of the house and none the least the energy system of the house. Instead of just focusing on the light that a window provides they focus increasingly on the functions that a window can provide as an integral part of the house. Overall, the companies are seeking to forward a broader and more integrated understanding on windows, energy efficiency, architecture and indoor climate than they have done earlier. Dovista/Velfac and VELUX are hence seeking to form a market standard that fits their own products better, by showing that it is possible to build a house that lives up to the standards of future energy efficient housing without compromising on light (or the number of windows) and indoor climate.

These strategic considerations means that the companies in the later years are actively involved as central partners in several green demo house projects under the title "Model Home 2020"[37]. In the recent project called *"Bolig for livet"* (housing for life) Velfac and VELUX are jointly building eight green demo-houses around Europe in the coming years based on their new vision combining energy, comfort and aesthetics. These buildings are aimed to

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[33] According to mail correspdance and interview with Ejner Jerking, January and February 2010, head of unit, responsible for policy making in the window area in the Enterprise and Construction Authority, part of the Ministry for Economic and Business Affairs.

[34] This section is based on interviews with Torben Hundevad , Dovista as well as www.dovista.com and www.VELUX.com/modelhome2020 and VELUX company pamphlets : Green LightHouse and Model Home 2020, 2009 and http://www.vkr-holding.com/.

[35] www.VELUX.com January 2010.

[36] www.VELUX.com January 2010.

[37] www.VELUX.com/modelhome2020

be: 1) CO2 neutral: the house gives more energy than it takes and uses only sustainable energy. 2) Comfort and Wellbeing: there is harmony between light/shadow, heat/cold and in-door/outdoor conditions. 3) Good indoor climate: Light, air and sound materials create comfort and good health. 4) Architectural wholeness: The house is formed in interplay between energy, comfort, and aesthetics. 5) Good economy: energy costs = 0 DKK. The first 3 houses have been built. The project aims to show that it is possible to live up to the high energy standards of to-morrow with 40 percent windows in the house.

To develop the active (as opposed to passive), smart, energy efficient house, innovations on the system level of the house have been necessary.

In cooperation with another VKR company called Window Master, specializing in computer systems to control the opening and closing of windows, they are working with an active heat/ventilation system. To this system sun-screens and shutters have been added that close in front of the window during the night. Sunscreens both help to control the solar heat of the house, but also reduce the airflow around the house, thus reducing heat loss. Also the shutters fulfill two functions in the system: first, they keep more of the heat inside the house during the night, and second, they reduce the problem of condensation on the windows.

One of the demo-houses is called GreenLightHouse which was built in 2009 up to the UN Climate Conference (COP15), see figure 4.2. It is Denmark's first public CO2-neutral building. Green Lighthouse is the result of pub-lic-private cooperation between the University of Copenhagen, the Ministry of Science, Technology and Innova-tion, the City of Copenhagen and VELUX and VELFAC.

Figure 4.2 The GreenLightHouse, Copenhagen

Source: www.VELUX.com January 2010

We will hear more on the technical aspects of the windows in these houses in the section on nano innovation among the Danish window producers later.

Overall, these projects illustrate a shift in competitive strategies from the window to the system level (the house) for these core Danish window producers, a shift forwarded by the stronger demands for eco-innovation. More advanced window innovations are becoming more strategically interesting, also of relevance for nano-solutions as we shall hear more about below.

4.6 Green nanotech – Activities and strategies among Danish glass companies

In this section we will shortly focus on the strategies and main nano-related innovation activities of the involved Danish glass companies, and how these relate to their eco-innovation and overall competitive strategies. The case is exemplified by the Danish division of the multinational company Pilkington Denmark, and the nano-dedicated upstart company Sunarc.

4.6.1 Nano strategies and coating technology at Pilkington Denmark [38]

In this case on Pilkington emphasis is not so much on the nano activities and products of the Pilkington Group, which is a major study of its own, but how Pilkington Denmark as a whole sale and glass processing company sees Danish developments and market trends for these products.

Pilkington, including Pilkington Denmark, officially does not use the terminology “nanotechnology” but rather refers to “coatings” as they have traditionally done. Pilkington, as most of the other big glass companies, have chosen to apply a low profile related to nanotechnology and there is no information on nanotechnology in their information materials. Partly because of the unsettled debate on nano-risk issues, partly because of the considerable uncertainty as to what is nanotechnology and what isn’t. A recent media storm related to a coating product with little effect has made the company more cautious. The product turned out not to contain nano after all but still Pilkington Denmark has received quite many reactions on this although the debate on the Danish product was even greater in Sweden.

According to Lorentzen, the competition on glass is hard and very technology oriented. Nanotechnology offers new opportunities in the coating area and forms an important part of the work in the Pilkington R&D labs as it does among all the large glass producers. Hence in the following we will look into the Pilkington coating activities and the demand for advanced coated glass products.

According to the company webpage “over the past fifty years Pilkington can claim to have been responsible for almost every major advance in glass technology”.[39] Pilkington spends around £33 million a year on research & development, which is undertaken by two globally, managed organizations within the two business lines, Building Products and Automotive Products. The coating R&D primarily takes place in the Pilkington main R&D department near the UK headquarters. The main coating plants are in Sweden and Germany where experimentation and production takes place. Additionally, Pilkington cooperates with the other R&D labs of the parent NSG Group.

A lot is happening on coating innovation in these years. The coating technology is going in two directions: the hard coating (applied on-line during glass production) and soft coating (applied off-line or ex post).

In Pilkington they have especially a competitive advantage in hard coatings, starting with this approximately 20 years ago. The hard coated products are today mainly attractive on the markets where the insulating glass manufacturers have problems in handling the more delicate soft coatings, e.g. among small producers in Eastern Europe or developing countries.

Pilkington has, as the other major glass producers, a great variety of advanced coated glass products within all the main functional categories. They have though no electrocromic glass. Today’s coatings are multi-layer coatings using different materials for the highest optical performance and for achieving multifunctional glass. Advances in computer modeling now means that the optical properties of coatings containing seven or more layers can be predicted. This leads to only minimal experimental trials needed before full scale production. And hence facilitates product innovation greatly.

The Nordic countries Lorentzen sees as being in the lead for new advanced glass products. They are quick to take up new technologies on the market. Pilkington has placed their greatest coating plant in Sweden because the Nor-

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[38] This section is based on an interview with Carl Axel Lorentzen in January 2009, head of Technical Customer Service in Pilkington Denmark, from autumn 2009 glass-advisor in Glasfakta Aps. Additional information is collected from the Pilkington webpage www.pilkington.com, Wikipedia and the report “Pilkington and the flat glass industry 2009 (Pilkington 2009) as well as reports on nanoconstruction: Nanoforum 2006, Elvin 2007, Broekhuizen et all. 2009.

[39] www.pilkington.com

dic countries are interesting markets for these products. Generally he sees the demand for advanced glass products as fairly similar in the Nordic countries. But it is also a small market; the Nordic markets together are half the size of the Polish market so their impact is limited.

On the other hand Lorentzen sees the window and wider construction sector as generally little innovative, also in Denmark. According to Lorentzen there is a serious lack of knowledge on glass amongst the Danish construction actors as well as experts in the knowledge institutions. Most of the experts are knowledgeable about energy efficiency but have limited insights into other functionalities of glass, such as none the least the quality of light.

Below a little more innovation specific innovation is brought with a main emphasis on self-cleaning glass, which was among the first well-known nanotechnological products in the construction sector.

Pilkington marketed the first self-cleaning window in 2001 which became world famous as an early commercial nano-consumer product; it is also It is the only publicly known nano product of Pilkington. The self-cleaning glass has environmental advantages in saving detergents, water and energy use.

Box.4.3 Self-cleaning glass products

There are four known brands for self-cleaning glass all based on nanotechnology, and all made by big players:

- *The Pilkington Activ* brand by Pilkington, the first self-cleaning glass from 2001. It uses a 15 nm thick transparent coating of microcrystalline titanium dioxide. The coating is applied by chemical vapor deposition.

- *The SunClean* brand by PPG Industries from 2002 also uses a coating of titanium dioxide, applied by a patented process.

- *Neat Glass* by Cardinal Glass Industries has a titanium dioxide layer less than 10 nm thick applied by magnetron sputtering.

- *SGG Aquaclean* (1st generation, hydrophilic only, 2002) and *Bioclean* (2nd generation, both photoactive and hydrophilic, 2003) by Saint-Gobain, applied by chemical vapor deposition. [12]

Source: http://en.wikipedia.org/wiki/Self-cleaning_glass, and company webpages.

These coated glasses clean themselves through photocatalytic decomposition in two stages. Exposed to daylight the "photocatalytic" stage of the process breaks down the organic dirt on the glass reducing the adherence of dirt to surfaces while making the glass hydrophilic (normally glass is hydrophobic). During the following "hydrophilic" stage rain washes away the dirt, leaving almost no streaks, because hydrophilic glass spreads the water evenly over its surface. For this reason the glass is also interesting because it remedies the rising problem with outdoor condensation on windows. As windows become very energy efficient the tendency to create condensation on the outside rises depending on the surroundings of the window and other factors[40]. Nano titanium dioxide particles are the preferred material of choice also in the Pilkington product because it is characterized by high photocatalytic properties, chemical stability and low price. The Pilkington Active product range is multifunctional and offers additional features like solar control and low emissivity.

The Pilkington self-cleaning glass has been a big flop, also on the Danish market. “The problem is that there is no regulatory demand for self-cleaning features. The market is driven by production costs while user costs are neglected, also by policy makers”. As the advanced glass products have their advantages in the user phase this is a major barrier for product innovation. The builder is typically not the one who is going to live in the house and have accordingly little incentive for product innovation”.

Lorentzen is not expecting this to change; he sees policymakers showing a growing interest into user issues related to environmentally friendly windows but little concrete measures to support this. The only new positive trends

[40] Pilkington Glasfakta 2009

he sees in the development of new quality levels for energy ratings (level 1,2, and 3 in 2020). In the upcoming Danish Building regulative noise is getting a new quality development and Lorentzen would like similar measures in other areas.

Low emissivity and solar control glass are standard in today's markets. The highest energy performance is achieved by soft coatings. Demand for energy efficient glass continues to rise; there are many areas, not only Eastern Europe but also e.g. the US, which are way behind in insulating glass and still primarily has one-layer standard glass in the current building stock.

The hard coating technology is particularly interesting in the area of glass for solar technologies. The market is booming in this area due to the strong climate agenda despite the economic crisis in construction.

The rise in advanced construction related to green demo houses in Denmark and elsewhere Lorentzen sees as playing an important role for advancing radical product innovations in glass and windows. Extraordinary technologies may be tested and more money is available in these projects. Pilkington is interested in participating in such projects in Denmark but have not yet found any suitable ones. Pilkington has discussed long term collaboration with the VKR Group but so far it has not taken place.

Lorentzen criticizes the other players in the construction sector for being hustlers, shopping around from project to project with little opportunity for knowledge accumulation. This practice he sees in contrast to their other main customer the car industry where long term R&D projects are standard. For this reason the construction industry is always behind the car industry in innovation, as illustrated by developments in glass and window innovation.

4.6.2 Sunarc Technology A/S - nanotechnology for anti-reflective glass[41]

Sunarc is a nano-dedicated upstart company specializing in the production of nano-structured antireflective surfaces on large size glass sheets; the glass is aimed for solar collectors and PV-modules and to a minor degree greenhouses. The idea is to minimize the light reflected by the glass to improve light transmission, especially important for solar technologies.

The technology used is, according to the company webpage, unique in the world. Passing several bathes the glass is submitted to a special etching process in a fully automated process. The resulting AR-surface is a nano porous structure of approx. 100 nm thicknesses on both sides of the glass. The chemical systems remain in a closed loop and no harmful waste is imposed on the environment. The result is a glass surface which releases six to eight percent more sunlight in depending on the glass slope. Hence Sunarc's products are an example of a fairly simple nanotech production process where the nanostructure becomes part of the glass itself rather than by adding a coating. In this way the glass can become nanoporous at both sides of the glass contributing to the high anti-reflectivity.

The company started its commercial operation in year 2000. After a slow start there has been a steady increase in the sale which the last years have exploded with the boom in solar technologies. 99 pct. of deliveries from the Danish factory are exported to Europe. In 2006 the company moved to new production facilities and the same year the company received Børsen's Gazelle award for being the second fastest growing company in Denmark. A new production line is planned which will increase the total capacity to about 3,5 million m2 per year. Sunarc is also planning to set up new plants in other regions of the world. So far a new plant has been made in Sweden and three in Singapore and more are expected as the demand is booming. The production facilities are not particularly expensive so it is attractive to set up production where it is needed close to interesting customers. The company has chosen not to patent its technology. Many have tried to copy what they are doing, also the big glass companies have experimented with this technology; but although lab scale production is easy, commercial up scaling is very difficult and Sunarc is still the leading full scale producer with this technology. The critical elements lie in the

[41] This section is based on mail correspondence and interview with Lars Albrechtsen, head of sales and marketing Sunarc, 2601 2010, and www.Sunarc.net , www.borsen.dk / gazelles and interview with Svend Svendsen, 0605 2009.

fine adjustment of the production process which is essential to achieve a uniform high product quality. Crucial tacit knowledge rests among core employees. Sunarc knows that competitors might emerge, but they expect to be well-established on the market and ready for the competition.

Sunarc is considering moving into low-E glass for general architectural use. They believe their technology could prove promising in the growing market for very energy efficient windows. They particularly see potentialities in improving the light transmittance which represents a problem in 3-layer insulating windows.

4.7 Green nanotech – activities and strategies among Danish window producers

In this section we will focus on the main nano-related innovation activities of the involved Danish window companies and how these relate to their eco-innovation and overall competitive strategies. Generally, nano innovation activities are as yet limited but there is an increasing interest among the involved companies. From the VKR Holding Group VELUX and Dovista and their supplier Superwood are the most actively involved companies in nanotech activities and are therefore getting the main attention here. Additionally the smaller PRO TEC company is shortly included as well as their supplier Fiberline.

4.7.1 Nano-strategies in VELUX and Dovista[42]

Nanotechnology has long been an aspect of interest to VELUX because it plays an important role among a number of their suppliers and in the components of their products. VELUX undertakes serious R&D in the area in order to be able to evaluate developments in the area, in part in a cooperation and dialogue with their suppliers. In this way they are ready to select the right products timely. As the mapping of Danish nano activities in construction showed (see chapter 2), VELUX is among the Danish companies with quite a varied interest in nanotechnologies. In the last ten years the interest into nanotechnology has grown in time with the general societal interest into nanotechnology. VELUX has so far participated in the nano innovation project the Danish “NanoPaint” project from 2005 to end 2009, which seeks to develop nanotechnological surface coatings.

The serious interest into nanotech trends and implications by VELUX is also reflected in their participation since 2006 in the nano background group of Danish Standards, which has a strong focus on risk issues but also work on characterization, metrology ect. VELUX is one out of only a handful of Danish companies who participate in this work. For VELUX the possible implications of nanotechnology for the environmental and health is a core issue to address. They see two poles in the nano community; one focusing on the health and environmental risks claiming nanotechnology is a risky technology, the other saying there is no problem and let’s get going with developing these promising technologies. VELUX tries to balance and find a middle way between these two poles but hopes that nanotechnology may come up with solutions to some of their enduring product problems.

Dovista (Velfac and Rationel) is so far little involved in nanotechnology but the interest is rising. They are continuously scanning their suppliers for new advanced solutions to their problems which include nano solutions; but there is no targeted search into nanotech innovations and they are only now beginning to become involved in specific nano R&D projects. As mentioned Dovista handles the R&D for Velfac and Rationel and therefore Dovista is the main level of analysis in this section, while VELUX has its own R&D department. The R&D coorporation between VELUX & Dovista is close; they draw heavily on each other’s findings and engage in common product developments both at the window and house level. Most of the innovation in these companies is about applying, combining and further developing technologies made by their suppliers than more fundamental research and development.

[42] Unless otherwise stated the following section is based on mail correspondence and interviews with Pia Tønder Mikkelsen, R&D Materials VELUX and Christian Wagner Insulating glazing units VELUX and Torben Hundevad, head of R&D, Dovista. Both VELUX & Dovista is part of the VKR Group.

The nano-innovation discussion below is separated into innovation related to glass (the pane) and innovation related to the frame and is structured according to technological themes. For the window producers it is the latter which has their main research and development focus, while the glass R&D is targeted at developing selection criteria for choosing which glass to buy in.

Nano-innovation in the pane

VELUX follows new product innovations in the glass business, in order to be able to select the right glass products for their windows. As the demand for still more product properties have grown, there is now coatings in most windows. Nanotechnology has formed a fundamental part of all coating developments in glass the last thirty years, long before the nano buzz word appeared. Hence nanoscientific insights are fundamental to the application of glass in VELUX windows.

<u>Self-cleaning/Low maintenance glass</u>

Since 2006 their sun tunnel has "easy to clean" as standard in some countries, while in other countries it is an optional choice on special types of VELUX windows.[43]. VELUX follows and investigates new easy to clean solutions from various producers.

<u>Low E and solar control glass</u>

Demands for high energy performance have been the core driver for glass product innovation the last 20 years and a lot has happened particularly the last five to ten years. While demands first occurred in Germany, today Low-E and solar control glass are standard on the markets VELUX sells to.

VELUX offers three layer insulating glass, however there is not much difference in the energy performance of good low-E two layer insulating windows and three layer insulating glass, especially if the windows are located properly towards south and west and a total energy balance calculation is made. The shift from the dark U-value towards a total energy balance perspective is hence seen as an important parameter to VELUX.

<u>Solar energy as thin films</u>

VELUX has varies solar products as part of their assortment, in shutters and curtains, but as yet they see the use of transparent nano-solar cells to be applied on glass as being at a very early stage of development and very far from a market breakthrough.

<u>Product innovation for reduced inside/outside condensation</u>

Dovista is engaging in a new nano R&D project which seeks to find novel solutions to the condensation conditions of their windows, composite as well as wood/alum windows. The nano project is a cooperation between a nanoscientist and an indoor climate scientist at the University of Aalborg and Dovista. The project aims to reduce the risk of both inside and outside condensation. As windows become well-insulated the risk for outside condensation is increasing. The risk for inside condensation is affected by a range of factors which the project is to investigate more closely.

Nano-innovation in the frame

VELUX's main R&D efforts lie in improving the frame and the closure system. Although wood is their most widely used frame material and considered one of the best materials to use in a window because of longevity and its structural specifications, to improve it by different treatments (paint and impregnation) has always been a core

[43] See http://www.VELUX.dk/Produkter

focus of the firm. Also metal protection is of key research interest to VELUX as they form important parts of their windows. Plastic, on the other hand, has less interest to them.

VELUX is currently participating in a nano innovation project, the "NanoPaint" project, which seeks to find, develop and test different nanotechnological surface coatings for wood, metal protection and plastic. The project runs from 2005 to end 2009, i.e. it is just finishing. In this project VELUX has been cooperating with nano scientists in the Danish Technological institute and University of Aarhus as well as product suppliers such as the Danish paint company Dyrup A/S, the Danish coating company Accoat A/S and Ciba Specialty Chemicals Danmark A/S. [44]

Figure 4.3. illustrations from the Nano-paint project

Source: http://www.dti.dk/inspiration/26342

In the NanoPaint project VELUX has particularly worked on two issues, nanopaint for wood and metal coatings. Additionally both VELUX and Dovista are working with nanotechnology for wood preservation, see further below.

Wood paint

In the NanoPaint project VELUX has cooperated in the Wood Group with the paint company Dyrops and nanoscientists from the Technological Institute to develop more durable paint for their wood frames. Via the project they have demonstrated that it is possible to encapsulate the biocide and thereby obtain a possible controlled release of the biocide. The effect of this controlled release of biocide is expected to affect the lifetime of the paint film leading to a more durable paint. While the other partners in the NanoPaint project are continuing cooperating on the product development also now after the project has ended VELUX will take part in further real life weathering tests which are needed in order to evaluate the long time effect that possible controlled release has on the lifetime of paint films which is still an ongoing issue.

Metal coating

The protection of metal from corrosion is a major challenge in many industries, also the window industry. Chrome VI has been widely used in many industries and some have been obliged to phase it out in 2009 because of the environmental problems associated with this. The construction industry has been given an extended time frame for out-phasing the product because of the longer longevity of building materials but as yet no definite date has been given. Hence all actors within construction are looking for alternatives, also VELUX. In the NanoPaint project VELUX cooperated with the coating company Accoat to look into possible nano-coatings, such as the so-called sol-gel coating Accoat works with. However, the project has not given VELUX major new insights on metal treatment. According to VELUX their main sources of know-how on nano-metal coatings remain their suppliers, the big international companies who provide the cold-coated metal products VELUX needs. These VELUX sees as being in front of the technological development also on nano coatings.

Wood preservation

[44]Nanopaint is an "Innovationkonsortium", meaning it is an innovation project supported by the Danish Ministry of Science, Technology and Innovation, see http://www.dti.dk/inspiration/26342 for a presentation of the project.

Another key issue for both VELUX and Dovista where nanotechnology already is playing a role is wood preservation. The companies have long been looking for more environmentally friendly wood preservation methods. In 2006 the VKR Group bought the small Danish nano-dedicated upstart company Superwood, who is pioneering the use of the so called "supercritical technologies", (see company case below), to preserve wood. This method does not use any heavy metals in the impregnation process as a contrast to conventional wood preservation processes which still present considerable environmental problems. In the autumn of 2008 VELUX and Dovista together began a R&D project with Superwood testing their new preservation methods on different types of wood.

They are currently engaged in further development of the product targeted specifically at the needs in window production. The idea is to use the supercritical technology not only to obtain durability due to anti-fungus treatment of the wood but also to obtain a water repellent effect. The results are so far very promising. The vision of the new window frame is that it should be very durable, rejective to unwanted growth on wooden surfaces and demand less maintenance. They plan to be able to start large scale production of the modified Superwood frames in a foreseeable future, but still more development work and tests need to be made. They already have the supercritical production capacity to undertake this up-scaling. This type of technology is unique in window production in the world.

The company Superwood – from upstart to part of VKR Holding[45]

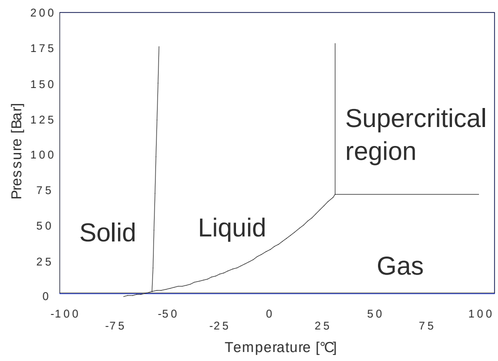
The company Superwood produces a new impregnation method by means of the nanotechnology termed "supercritical CO2". With the patent from 2001 Superwood made the world's first complete preserved spruce protected all the way into the kernel. This gives the boards a substantially longer lifespan while presenting an environment-friendly alternative to traditional products. The method has proven capable of significantly reducing problems related to the environment during wood impregnation. By using this method, the use of chemicals per m3 wood is significantly reduced compared to conventional methods, and the use of heavy metal salts and boric acid is avoided. By using supercritical CO2 as a solvent, the use of organic solvents is also avoided. In addition, the method has numerous advantages. The wood is completely impregnated and can be processed without exposing un-impregnated wood; the method enables the impregnation of wood species such as spruce that cannot be impregnated using traditional methods; and the wood may be used immediately after the impregnation since the process leaves neither large amounts of water nor solvents in the wood.

The Superwood company was started in 2002 as a buy out from FL Schmidt (similar to SCF Technologies a little later, see also section 4.1.1 on the company Photocat), then known as Supertræ. The purpose was to focus on environmentally friendly wood preservation through supercritical technology based on their world patent filed in 2001. The production was and is unique in the world. The young company, which had six different owners, struggled with up scaling the technology and in 2003 the company went bankrupt. In the search for new owners VKR Holding appeared as the most interesting option being resourceful and innovative which was just what the new company needed. In the VKR Group the company benefits from the enlarged R&D cooperating with the VELUX and Dovista R&D people as well as a shared new wood scientist. Torben Hundevad, head of Dovista R&D is on the board in Superwood. But the company has also benefitted from a lot of practical support service, such as accounting, IT support etc. The company thereby has gained better opportunities to concentrate on the development of their production process and products. The company keeps up its high R&D profile, e.g. currently having 1 PhD. project going.

The Superwood® production process
The wood preservation is brought into the wood by using so-called supercritical technology, or supercritical CO2.

Figure 4.4 Phase Diagram for CO_2

[45] This section is based on mail correpondance as well as interview with Ole Dalsgård Nielsen, ceo of Superwood A/S January 15 2010, and www.superwood.dk, and www.SCF-Technologies.com



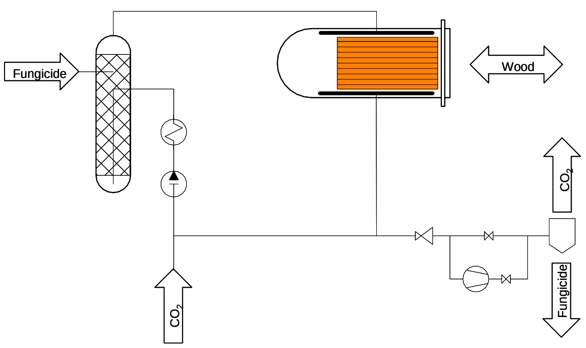
Source: Figure supplied by Superwood A/S

The supercritical technology uses high pressures and temperatures to convert organic materials in chemical reactions in water thereby developing nanostructured materials with new properties. At high pressures and temperatures, there is complete breakdown of organic matter into individual molecules. These molecules react chemically with the water, and with a suitable catalyst the reactions can be controlled to provide a very specific product. High pressure carbon dioxide – also known as supercritical carbon dioxide – is an intermediate stage between a gas and a liquid with special properties. It has an unsurpassed ability to penetrate most porous bodies due to its gaseous viscosity and its great ability as a solvent due to its liquid-like density. Chemical reactions occur rapidly because the molecules in supercritical carbon dioxide move rapidly in the same way as in a gas. The technology based on supercritical carbon dioxide is well suited to either remove or add certain compounds at the molecular level without the product losing its characteristic properties.

In the case of Superwood the carbon dioxide is put into a mode where it acts as a vehicle for antifungal agents. The solvent can penetrate right into the heart of the wood. The carbon dioxide is emitted again and reused. After the impregnation process, the tree has the same natural properties as before treatment and is ready to work with. The actual impregnation process is pretty simple:

- The wood is placed in the impregnation vessel
- The required amount of active ingredients is placed in a mixing vessel
- CO2 is added, and pressure and temperature are adjusted to the desired condition, whereby the active ingredients are dissolved in the CO2
- CO2 together with active ingredients is circulated through the impregnation vessel for a suitable period of time, thus ensuring an even distribution of the active ingredients in the wood
- The vessel is depressurised whereby any excess active ingredients are deposited from the gas, enabling both CO2 and the active ingredients to be recycled.
- The wood is removed from the impregnation vessel and is ready to be used.

Figure 4.5 Flow Sheet for Impregnation plant



Source: Figure supplied by Superwood A/S

Since the solubility of water in CO2 is very limited under the conditions under which the impregnation takes place, the process does not change the moisture content of the wood.

Market development

Superwood is also, as before the takeover by VKR, marketed to timber trades. The sales are developing positively which the company sees as a consequence of the rise in demand for green products. In 2006 7 Danish timber trades were stockiest on Superwood, in 2007, the number rose to 35, in 2008 to 60 and finally in 2009 the number of stockiest timber trades reached 120. In just four years the Superwood product has become a market standard in e.g. cladding and decking boards, despite the fact that the product is new and builds on a technology which is unknown both to consumers and professionals. The product has not been marketed abroad yet. The company has great market expectations to the upcoming modified version of the product.

Available amble supplies of Scandinavian spruce and distribution by Sweden's largest privately owned sawmill group Vida Wood offers good production conditions. While the product is marketed as a green product it is only known to be used in one green demo house, an “active house” kindergarten to be built by the VKR Group in 2010.

Plastic Composites

When it comes to plastic composites, it is the Dovista/Velfac entity which has been the most active in the VKR Group. DOVISTA/VELFAC has considered composite windows for many years, none the least due to dialogues with the Svend Svendsen group at DTU. Since 2007 DOVISTA/VELFAC has been engaged in developing better, more energy efficient window frames with the help of composite materials. Dovista/VELFAC initially tested more than 200 materials but did not find that the materials were capable of combining the required characteristics. Therefore Dovista developed Helo-Fibre in conjunction with leading material suppliers in Europe and North America. Helo-Fibre® consists of PUR (polyurethane) strengthened with thin glass threads. Helo-fibre is not only particularly suitable for the production of weather resistant low energy windows in high quality; the material is distinguished by the ability to be produced with a uniform surface. On the basis of its strength the material can be used in very slim constructions and in very large sizes. This gives the possibility to develop windows with a large unhindered daylight intake. The material is being used in the frame and sash of the window.

The vision behind the window is to develop an energy+ window that supplies the buildings with more heat than is disappearing and that complies with the strict energy requirements of the future for both new buildings and renovations. The window contributes positively to the energy balance with regular 2- and 3- layer glass. Helo supports both the low-energy house concept by using under 15 kWh/m^2 and the active house concept where the house produces more energy than it uses.

Dovista has filled a number of patent applications. Currently, the basis product has been successfully developed, and is being tested since 2009 in the recent green demo houses of the VKR Group in Denmark and Austria so far, i.e. in the Bolig for Livet project. In these houses the frames are used in three layer insulating units. The windows are filled with argon, as a very high energy performance can be achieved without the much more expensive krypton.

Dovista continues the product development and hopes to have a new improved window frame product ready for full scale production within foreseeable years. They are awaiting sufficient tests on the properties of the new window before a full market release will take place. They want to avoid a new “eternit case”[46], and be absolutely sure

[46] Eternit was used in roofs but displayed major problems and is no longer used.

that the new window has the durability and other properties as promised. The new composite frame contains no nanotechnology as such.

4.7.2 PRO TEC Vinduer A/S and Fiberline A/S [47]- composite window production

PRO TEC Windows was founded in 1993 focusing on the production of alum-wood windows. In 2003 PRO TEC participated in the competition ”The windows of the future for the houses of the past” launched by Danish The House owners Investment Fund (“Grundejernes Investeringsfond”) together with the architects Friis & Moltke. During this project they identified the composite material, GRP (glassfibre reinforced plastic) as a promising material for producing more energy efficient and elegant windows. The next 3½ years the company continued the product development involving collaborations with an architectural company, as well as the composite supplier Fiberline Composite. Seven people from PRO TECs internal R&D department consisting of designers, architects and engineers worked solely on this project in this period. Svend Svendsen’s group at the Danish Technical University, DTU contributed with advice and energy calculations. Finally in 2007 the company launched PRO TEC 7, the first composite window to enter the Danish window market. Fiberline was involved in the project and the development of the profile designs and is now the supplier of these for PRO TEC.

PRO TEC 7 is being patented by PRO TEC windows. PRO TEC continues to develop custom-made solutions collaborating with architects and construction companies in several countries. They have especially orientated their sales towards glass facades as well as low energy buildings. According to their webpage they are “reinventing the window” and are “building with energy in mind”.

The product

PRO TEC 7 has very high insulation properties. The U-value for the total window structure is as low as 0.51 W/m²K, which puts the window well ahead of the tighter new specifications introduced in the upcoming Danish building regulations. Looking at the energy balance it is an energy plus window, producing up to 11kW/m2. The energy performance of the window can be increased by up to 60% compared to traditional modern low energy windows. [48] The frame appears sleek letting in a large amount of light. PRO TEC also produces integrated façade systems without double frames. The composite window is 20% more expensive than traditional windows, but the total cost of ownership is far less than for a traditional window giving the energy prices.

Their most recent initiative in environmental strategy is to enter into an alliance with the Danish companies DONG Energy (energy advice), Rockwool (insulation) and Danfoss (heat pumps), offering a building energy renovation package to consumers.

Fiberline Composites is a Danish high-tech company producing advanced composite materials as a component supplier. Since its establishment in 1979 the company has played a major role in pioneering new GRP (glassfibre reinforced plastic) applications within construction. Fiberline is today Europe’s leading manufacturer of GRP profiles. Fiber line’s R&D department is staffed by experts in composite mechanics and polymer chemistry supported by technical personnel with knowledge of the pultrusion process used in the GRP production. Fiberline has a pultrusion line dedicated to R&D. From early on, Fiberline has aimed for the production of profiles for the wind energy industry as well as structural and architectural applications, such as GRP based lightweight bridges and buildings as well as (GRP) composite windows, facades and doors. In 2004 they became involved in developing profiles for window frames together with PRO TEC and are supplier of GRP window profiles for PRO TEC today. Fiberline Composites also develops window frame profiles to several leading European window manufacturers.

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[47] This section is based on mail correspondence with Finn Jernø, head of communications, Fiberline, and Nikolaj Haulrik, Sales & Marketing Director PRO TEC, and interview with Svend Svendsen, DTU, 0605, 2009, 0601 2010, Kristian Koldtoft, Fiberline 1101 2010, and http://www.fiberline.dk/ and http://PRO TECwindows.com/en/pro_tec_7/Product%20information.aspx

[48] http://PRO TECwindows.com/en/pro_tec_7/Product%20information.aspx

The current composite material is not nano-enhanced. Fiberline was active in three minor nanotech development projects a couple of years ago looking into possibilities regarding durability, optimization of flame resistance and self-cleaning of the surface. The company keeps an eye on nano coatings to obtain properties such as anti-graffiti and anti-fungi which are wanted in windows and construction parts. Not at least when it comes to facades.

The development into window production has been a gradual one. When the production started in 1979 both the composite material and the pultrusion production process were unknown and the company had numerous dialogues with companies from many sectors, seeking to find interesting application opportunities. Fiberline argued that they had a new material with unique properties in unifying high strength, low weight, no corrosion in outdoor conditions, and a good insulator for heat/cold and electricity. At the same time a product where it is possible to make solutions highly tailored to the requirement of the customers.

The window and facade industry abroad began to take an interest into the thermal properties and the possibility for breaking the thermal bridges in the late 1980s. For twenty years Fiberline has delivered different kinds of thermal breakers as well as reinforcing components for this industry abroad. The last ten years the demand for energy efficient windows has grown, and Fiberline Composites has been able to commercially exploit the knowledge they have developed within this field. It has therefore been a natural development to expand the production of profiles into more window parts or entire window or facade frames.

Fiber line’s GRP profiles for window sills and frames are developed in close cooperation with their customers, the window or façade producers. However, they have also made prototypes of windows and facades themselves, either alone or in cooperation with universities or architects. Fiberline made the prototypes in order to illustrate that profiles of GRP are well suited for window sills and frames. Fiberline cooperates with a large number of international and Danish universities within the areas of composites, heat loss and windows/facades. Their factory is in itself a gigantic showroom, where their customers can see a wide array of examples of GRP window and façade products made of Fiberline profiles. Their profiles and prototypes of applications have won a number of design prizes. By now their GRP composite material is a recognized technology with new design opportunities.

Fiberline has just received public funding from The Danish National Advanced Technology Foundation for a new window research project. It aims to create new profiles for composite window frames that insulates twice as well as the best frames and sills on the market today. The project takes place in collaboration with the Department of Mechanical Engineering and Civil Engineering at the University of Aalborg.

The market demand for composite windows

Both companies state that the demand for composite windows has gone up during the last few years and the market is all together developing very well despite the financial crisis. According to Fiberline Composites the early interest for composite windows came from Germany, Austria and Switzerland. The building requirements in these countries are clearly ahead of those in Denmark, but there has been a gradually rising interest first of all within the EU region. Clearly, the window producers need to develop products with lower U-values to live up to the new and coming building requirements. It is the most innovative and development orientated companies who start producing the new high insulating windows.

Further down the chain they see a more general attention to energy efficiency, climate issues and demands for heat loss calculations in buildings among their customers, while the consumers are less conscious of thermal bridges. The engineering companies, and in part architects, are responsible for making the heat loss calculations which increases their interest in energy efficiency issues and components. Often the low energy demand comes from the builder, either the private or lately also the municipalities. There are now approximately ten climate municipalities in Denmark, and they are often ahead with the new energy efficiency demands, at times they parcel out energy plots of land.

4.8 Green Nanotech - activities and strategies among companies with complementary assets

This section brings a case on the green nano strategies and activities of the Danish upstart company, Photocat A/S which so far has had limited interaction with the other actors in the window chain.

4.8.1 Photocat A/S – a nanodedicated company within photo catalysis

Photocat A/S is a new Danish company established in July 2009 which develops and markets advanced nanostructured materials and coatings.[49] Before this dates the activities of the company was part of the likewise young Danish company SCF Technologies A/S. Photocat was started by three former SCF employees, two nanoscientists and a senior leader. SCF Technologies have acquired a considerable part of the shares and hold for the time being 50 pct. The new company specializes in advanced materials with photocatalytic properties, e.g. self- cleaning functions. The firm has one product directed at the glass market, ShineOn® Pro which is an aftermarket treatment to make window glass self-cleaning. The rising business area of the new company is photocatalytic materials for indoor floors, the ActiFloor product line. The idea is to make floors which are depolluting and thereby improve the indoor climate as well as being easy-to-clean.

History

Although Photocat is a very new company its development activities build on years of experience from the activities within the original company SCF Technologies. SCF Technologies (SCF) is a small nano-dedicated company established in 2003 as a management spin out from the Danish construction company FL Schmidt, similar to the case company Superwood (see elsewhere). SCF defines itself as a knowledge intensive company dedicated to product development rather than marketing activities. Once products are being developed they are sold to companies nearer the market via licenses. Hence SCF undertook major R&D activities in its first years, trying to develop nanostructured materials with new properties based on the so called “supercritical technology” (See the Superwood case for further information on the technology). Already 12 patent applications have been filed. The company cooperates with nano science institutions, noticeably the iNano science centre at the University of Aarhus (one of the biggest nano science centers in Denmark), which has been essential to allow for sufficient nanoscientific laboratory access. SCF builds on basic nanoscientific insights as well as insights in the specific supercritical technology which dates 20 years back via core employee’s work in FLScmidt.

The fundamental nature of the supercritical technology means that it can be applied to a range of widely different areas. Hence SCF experimented with a range of application ranging from cleaning of wine cork (which is now a commercial product but licensed) and fat removal from potato chips but formed relatively quickly the two business areas Advanced Materials and Energy. In the energy area the activities centered on bio-oil from organic waste which by now is the core focus of the remaining SCF Company. In the advanced materials area work quickly concentrated on self-cleaning glass.

The idea for the glass product was inspired by the nano wave in the early millennium; another Danish nano company made anti-stain products on textiles and marketed these aggressively in Denmark around 2006 and 2007 becoming the first well-known nano product on the Danish market. One of the SCF founders thought that SCF could make a similar product but applied on glass. In 2006 they made their first product TailorMat based on imported nano-material from China. The idea was to add this fluid to a tissue to be used for polishing windows aim-

[49] This section is based on mail correspondance as well as interview with Michael Humle, CEO of Photocat 2001 2010 as well as company webpages; http://www.shine-on.com; http://www.tio2uk.com/; http://www.scf-technologies.com/ and Andersen and Molin, 2007.

ing at consumers through gas stations. The product was licensed to a German company – Innovate GmbH who should produce, sell, and market the treated tissue. The plan was to start commercialization in 2007 on the German market. However, SCF encountered a number of technical challenges regarding the product. It was, amongst others, difficult to make the fluid stay stable in the tissue.

Below is a microscopy picture of untreated glass and the same glass surface treated with TailorMat. The surface treatment evens out the invisible microscopic cavities in the surface of the class and provides the glass with a self-cleaning effect

Figure 4.6. A microscopy picture of untreated and treated glass

Source: www.SCF-Technologies.com

As the problems with the first product became clearer the advanced material group of SCF began work to design their own nanoparticles in 2005. This work is not based on supercritical technology but rather on basic nanoscientific insights in photo catalysis. Using pear mill technology wet grinding of materials from micro- to nano-range takes place. The basic technology developed consists of making and configuring sets of nanoparticles. The main constituent is Ti02 nanoparticles but other elements are added. The technology has been patented; altogether Photocat now has five patent applications in the process. In 2007 the SCF company reached an important step in consolidating all its operations (laboratories, test facilities and personnel) under one roof and expanding to 35 employees. Work with the bio-oil developed positively in cooperation with the big and innovative Danish machine producer Grundfos. However, still commercial breakthrough was awaiting.

In 2008 the attempt to license the first product to the German company was finally given up. The commercialization of the product in Germany did not produce the expected results. The interest of SCF in self-cleaning products fell as the young company had urgent needs to find commercially successful products. As the bio-energy product developed successfully their interest in concentrating on this area grew further.

In the mean time the employers working in the advanced material group continued their work. They had Danish Technological Institute conduct an independent test of the new ShineOn® product in its modified form which verified the product's self-cleaning properties. From an encounter with the director of the Swedish floor company Välinge Innovation in 2007, new ideas emerged within the group to produce depolluting floors to improve the indoor climate. The idea was to make floors become active formaldehyde and VOC filters. Välinge appeared an interesting innovative partner having pioneered work within easy to assemble laminate floors, avoiding the use of glue.

Together with Välinge they developed a new patented composite floor, ActiFloor, where photocatalytic nanoparticles are integrated in the matrix of the upper layer. As far as Photocat knows the product is the first of its kind in the world. Although the main constituents are the same as in ShineOn the configuration of the set of nanoparticles differs. Here the challenge was to develop a set of nano particles that could provide sufficient photocatalytic activity to perform in indoor visual light as well as being integrated in a composite matrix. By early 2009, the project had reached proof of concept and was presented on the Domotex 2009 exhibition in Hannover. In the summer of

2009 the product was presented to the first three customers. This formed the basis for founding the company Photocat on the 31st July 2009. A verified test has showed that the Actifloor can eliminate formaldehyde release from the floor itself, but also from other sources such as particle boards, furniture, smoking in the indoor air, reducing formaldehyde emissions with 98 pct. The ActiFloor treatment is incorporated into the matrix of the floorboard giving it additional features like easy-to-clean with quick dry effect and no streaks or spots. The two companies have formed a new IP company – Välinge Photocat AB. Together the two companies will market Active Floors based on composite materials.

The new company is currently placed at the Symbion Science Park in Denmark, which provides a good stimulating knowledge environment. There is no cooperation between Photocat and SCF, but the CEO of SCF is on the board of Photocat. The company plans to start up-scaling to industrial production in its new production facilities in Sweden (Helsingborg) already in summer 2010. They are not expecting any problems in up-scaling their production methods. They are working closely with their equipment supplier, the German NETZSCH Grinding & Dispersing, who are competent within nanosized pearl mill technology, to bring Photo cat's patent pending milling technology to a commercial production level. The production has gradually been refined and made ready for more industrial implementations, so far the mentioned floor product.

The ShineOn product

ShineOn is marketed as a green product which reduces chemical usage and water consumption as well as being cost effective as it reduces the customer's window polish bill. Photocat's current (2. Generation) product to the professional wholesalers consists of education and two fluids as well as a set of recommended spray containers. ShineOn is applied by professionally trained people in two stages. First a polishment and afterwards the photocatalytic layer is sprayed on by a handheld spray. To ensure safe and correct handling the product is only being marketed to professional customers among glaziers and renovation companies under the name ShineOn Pro. Photocat recommends that application is done by professional actors wearing safety equipment. ShineOn is by now being marketed by license to whole sale companies in the UK (TiO2 Ltd.) and the US (ISP Painting Inc.).

Important to Photocat's competitive strategy is documentation on all of its products. There has been too many stories of anti- stain or self-cleaning nanoproducts which turned out not to work effectively or which were not nanotechnology after all. ShineOn is, as mentioned, tested by the Danish Technological Institute in 2008 verifying that the product was indeed self cleaning according to European Standard. The cleaning capacity equals the one of the well-known Pilkington and Saint-Gobain brands. It takes up to 5 times as long to apply ShineOn Pro compared to traditional window polish, but the effect is also much more long lasting. While tests have showed that the photocatalytic effect is estimated to last at least 7 years Photocat only promises the windows to be self-cleaning for two years. Then the treatment may be repeated.

An important part of the documentation is on health and risk issues related to nanoparticles. All their products have full material data safety sheets made in cooperation with experts in the area and in compliance with regulation in the area. Photocat is also attentive to the Danish research in the area. They consider that since their indoor products are integrated in a matrix the exposure to inhalation will be minimal. The director is skeptical towards the general risk discussions related to the very diverse nanotechnologies, and calls for the need to make individual product estimations.

In Denmark marketing activities have been limited and no license partner has been found. During the development stage contact was taken to Dovista which tested the first version of the product, but they did not find it satisfactory. Because of this less successful event no further contact to Danish glass and window industries has been tried. A meeting was sought established with the Danish Glazier Guild but it was never carried out due to lacking interest from the SCF company at that time. Photocat now awaits the commercial result in the UK and US markets before further costly marketing activities are being taken. Since the core business focus increasingly is in the upcoming floor product area, the glass product area is currently receiving somewhat less attention.

Photocat has not considered developing multifunctional glass coatings with energy control properties. In principle the ShineOn product could also be used indoor for VOC control on varies glass facades, but as Photocat says, there is no rain indoor, but possible applications could be considered. Health issues may be an issue here though with the spray technology.

As Photocat appears today the company markets itself as a clean-tech company which makes green products but with a rising focus on the indoor climate. The argument is that the more buildings seek to reduce their carbon footprint, the greater is the indoor climate problems and the need for VOC control. The company argues that the indoor climate issues have been neglected in the climate debate, also in Denmark. E.g. the permitted Danish limit for formaldehyde lies at twice the maximum level recommended by WHO. According to Photocat the Danish State Building Research Institute has measured that the Danish high levels in many newly built houses have been exceeded. The company expects to expand its portfolio of building components with photocatalytic properties further particularly aiming for indoor climate improvement.

4.9 Conclusions: Effect of green nanotech on Danish industrial dynamics and strategies in the window chain

The Danish case on green nanotech development in the Danish window chain has sought to analyze nano- and eco-innovation processes partly at a company strategy level (e.g. Teece, 1986, Langlois, 1999, 2003, Chesborough, 2006), partly within a wider national innovation system analysis (e.g. Lundvall, 2002, 2005, Malerba, 2005). Two parallel market phenomena have been studied: the emergence of nanotechnology and the emergence of the green market. Clearly, eco-innovations and nano-innovations have co-evolved along the transformation of institutions and organizational changes on the market. The institutional setting has played a significant role in window innovation, none the least for facilitating eco-innovation. It is not surprising that policy has played a crucial and very direct role for the innovation going on in the window chain. But it is more interesting that core scientists in knowledge institutions, and in part green NGOs, have played important roles in promoting more radical eco-innovations in window production. This has happened both in direct ways (dialogues with companies) and indirect ways (influence on policymaking). Clearly, also the companies take an effort in seeking to influence policymaking in an area such as this with very strong policy effects. The public debate has also been important, both on consumer issues (energy efficiency, product quality, indoor climate) and risk issues (nano-particles and health and environmental effects).

The innovation system perspective is important also in shedding light on the emergence and role of underlying knowledge bases on respectively eco-innovation and nano-innovation and the knowledge bonds and flows between companies as well as with knowledge institutions.

The analysis has shown seven main empirical findings:

1) The impact of nanotechnology in the Danish window chain is surprisingly high and pervasive given the low expectations to the absorptive capacity of the construction sector towards nanotechnology. Nanotechnology takes part in quite a large number of important innovations in the Danish window chain though far from all. Nanotechnology is often sought applied to enduring problems where existing technologies fall short.

2) The rising strong demand for eco-innovation in construction is the perhaps most important driver for nanotechnology applications. There is a marked shift towards more systemic and smart/active eco-innovation strategies, a trend which fits well with nanotechnological opportunities. Most noticeably, the window companies are changing their roles on the greening market increasingly taking on a role as system integrators and hence producers of green buildings rather than green windows.

3) Both incumbents, upstarts and the really big multinational companies play important but different roles in the development and uptake of nanotechnology: The multinational glass producers but also the big chemical and metal material suppliers act as core nano-technology developers. The main medium big players in the Danish window industry show a considerable absorptive capacity towards nanotechnology with widespread nanocapabilities, but

also play a surprisingly active role in actual nanotech development in the frame area. In their rising roles as system integrators in eco-innovation in construction, the window industry seems to be able to pull in a variety of nanotechnologies and may become important carriers of nanotech capabilities more broadly. The nano-dedicated up-start companies are, as expected, important nano-technology developers of new niche markets.

4) Overall, all companies display a cautious and discreet if not secretive strategy towards nano-marketing. However, particularly the dedicated nano upstart companies are more positive in their nano-marketing. The big multinationals are the most reserved being very careful to PRO TEC their reputation. Nano-risk issues to health and the environment are overall dealt with carefully and methodically by the companies. As a result of the discreetness, however, there is quite a lot of nanotechnology applied in the window chain that is not communicated very clearly and is not widely known. Part of the discreetness is, however, not due to risk aversion but due to tradition. Exactly because nanotechnology has been around in glass production for so long and preceding the rise of the term nanotechnology, the concept is not widely used in the sector, which prefers, as traditionally done, to refer to "coatings". Overall, the reserved nano-branding is interesting and reflects a decline in the nanohype on the market compared to the beginning of the millennium. Only companies really dedicated to nanotechnology now brand themselves with nanotechnology. The reserved attitude may mean that search into nanotech opportunities are somewhat restricted by some companies and that some nanotechnological opportunities will not be utilized.

5) The opposite is the case for eco-innovation which is experiencing the strongest hype ever. The search for green market opportunities is intense among all kinds of companies in the window value chain and the rise of a green economy is clearly felt.

6) The Danish case shows quite a varied sample of nanotechnologies illustrating clearly the diversity of the nanotechnological conglomerate in the currently very fluid stage of technology evolution. Many of the more interesting developments in the downstream part of the chain (post the glass manufacture) window are though, of a relatively recent date, illustrating that we may be experiencing a rising commercialization in nano-enabled construction.

7) The policy regime has only partially stimulated innovation. While regulation on energy efficiency towards buildings certainly has been a core innovation driver, it has also restricted innovation. The change towards more flexible policy measures in recent years both internationally and nationally is stimulating eco-innovation stronger, and is particularly forwarding more systemic eco-innovations.

Overall the study contributes to our understanding of eco-innovation dynamics as well as nano-tech dynamics. Clearly eco-innovations currently are in a decisive historic phase of rapidly growing market acceptance and consolidation. Eco-innovation has become mainstream and companies are seeking new niches to position themselves on the greening markets. New market opportunities are emerging as eco-innovation is no longer narrowly defined by the reigning policy regimes. These new opportunities in the window case show strong systemic features. We see an interesting strategic shift in the move from the main incumbent Danish window producers from window (or building component) producer to (green) building producer. The window companies are increasingly functioning as system integrators and market makers. They are forcefully trying to set a market (and partly also a policy-) standard for green houses that fits their products. At the same time the up-start companies are trying to establish niche markets for new green (nano)-products. With the current strong demand for green products they seem to be experiencing a relatively easy market access. However, the incumbents are also showing the will and capacity to innovative radically but, as stated, at the more systemic level, redefining the green house and sustainable living.

Today, the Danish window case illustrates that for all actors in the window chain, it has become a necessity to have a high green profile and to be able to find new business opportunities for eco-innovation. It seems nanotechnology may play a rising role in the search for novel eco-innovations if sufficient attention is given to the green opportunities and not only the risk issues associated with nanotechnology.

5 Emerging value chains: The case of Finnish coating technology and glass manufacturing

5.1 Introduction

The construction industry can more appropriately be described as an industrial cluster as construction projects rely on inputs from a whole range of different industries. The industry comprises multiple value chains which supply various components, elements and services which are integrated into a whole by the construction companies in the downstream segments of these value chains. Especially glass-processing, and related machinery, is also an area where Finland has a long tradition and deep competencies as an illustration of an application field for nanotechnology outside the commonly touted `high-technology´ industries, e.g. ICT and health care.

The methodological approach used in the case studies has been qualitative face-to face interviews. The primary aim of the interviews has been to identify opportunities for nanotechnology-related eco-innovation in the Finnish construction industry, with glass-processing and windows as an example. In order to include the viewpoint of as many relevant actors as possible the first part of each interview was dedicated to identifying examples of core actors in the value chain, including core companies in supporting and adjacent industries as well as relevant public sector actors (this resulted in Figure 5.1 as introduced below). The interviewee subjects were then chosen to represent each segment and part of the value chains (each box and row in Figure 5.1). The remaining parts of the interviews focused on drivers, facilitating and inhibiting factors, for the industrial uptake and commercialisation of nanotechnology.

Altogether 16 interviews were undertaken during 2007, see appendix 4 for a list of interviews. They were recorded and analysed during autumn 2007 and spring 2008. Web-based searches and enquires were undertaken during spring 2009 to ensure that the company descriptions and main findings of the report remained up to date.

5.2 Core actors in the value chain and their nanotechnology involvement[50]

The Finnish construction industry, here defined as a cluster of supporting machinery, services and related industries, employs some 500 000 people (the total population of Finland is 5 300 000) and is thus a significant economic sector. In terms of output the estimated total value of construction in 2007 in Finland was EUR 27.4 billion, while the construction product segment contributed with a volume of EUR 7.9 billion during the same year (Confederation of Finnish Construction Industries, 2009).[51] Based on data from 2005, output of the construction industry can be broken down by primary construction materials. By this breakdown the metal products contribute with the largest share of 36 percent followed by wood products (26 percent) and stone products (19 percent). The remaining share is accounted for by various other construction products, such as those related to glass-processing and windows as the focus of this report.

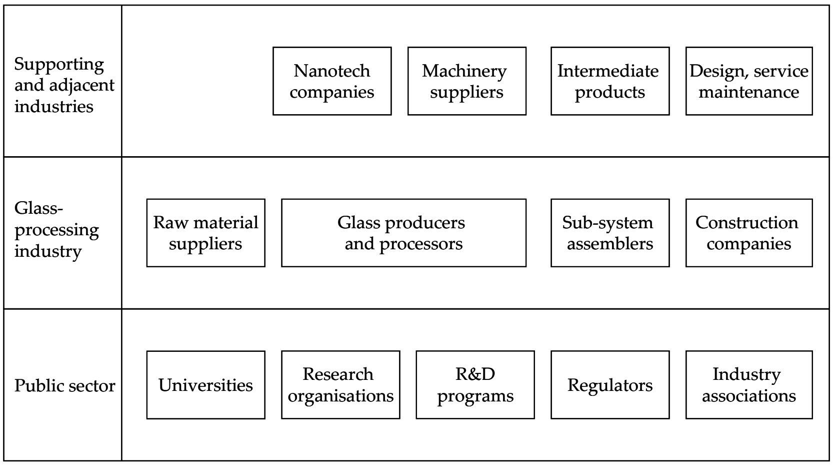
[50] The Finnish case study has been published earlier in its entirety as ETLA Discussion paper No. 1191 (see http://www.etla.fi/files/2318_Dp1191.pdf).

[51] http://www.rakennusteollisuus.fi

Apart from Pilkington Finland, the Finnish branch of one of the four major global companies, the glass-processing industry is populated by smaller companies in the field of container glass, household and art glass using other processes. The contours of the Finnish glass-processing and window value chain, including supporting and adjacent industries, as well as relevant public sector organisations, are illustrated in Figure 5.1.

The central value chain of the glass-processing industry is illustrated in the middle row of the figure, while supporting and adjacent industries are in the top rom. The nanotech companies, of interest to this report can be considered as part of the supporting and adjacent industries; they exemplify one route for the renewal of the construction industry when considering the role of new materials (other routes relate e.g. to ICT). The bottom row illustrates public sector activities and organisations, some of which also contribute directly to the development of eco-efficient nanotechnologies.

Figure 5.1. The glass-processing and window value chain in Finland



Source: own source

The first segment of the central value chain of glass-processing and windows production composes of *raw material suppliers*, such as Partek Industrial Minerals and SP Minerals as the main Finnish supplier of quartz, the primary raw material for glass. In addition there are also some other specialized raw material suppliers of relevance to nanotechnology applications. The *glass-producers and processors* are next in the value chain, and these companies have an important role to play in the application of nanotechnology as they master the capital-intensive flat-glass process as the dominating one in the industry today. As this segment of the value chain is dominated by a few global players – namely Nippon Sheet Glass (NSG)/Pilkington, Saint Gobain, Asahi or Guardian – it seems that the application of nanotechnology has to involve one or more of these companies. NSG/Pilkington is a particularly interesting company in this context as this company has production activities in Finland (Pilkington Finland and the Lahti factory). These production activities also included a float-glass factory until June 2009 when the economic crises lead to its closure. The current economic crisis has also significantly affected other glass-producers, processors and sub-system assemblers.

5.2.1 Pilkington Finland

Pilkington Finland only constitutes a small unit of NSG/Pilkington, employing 1200 people primarily at the factories in the towns of Ylöjärvi, Lahti, Nivala and Tampere. Pilkington Finland focuses on automotive glass, but also produces glass for the construction industry as well as speciality processed glass. Overall the R&D activities of NSG/Pilkington is organised centrally close to the headquarters in the UK, while the Finnish unit primarily has been involved in production. Nonetheless, the Lahti factory has had a certain strategic role in the overall R&D

activities of NSG/Pilkington as it has been an advanced pilot factory especially well suited for the production of thinner glass sheets, also called micro float.

NSG/Pilkington is a technologically advanced company with a long history of technology development and innovation, not least as exemplified by the invention of the float glass process in 1959. This company has also been an early mover in nanotechnology through the introduction of Pilkington Activ, the world's first self-cleaning glass introduced in 2001 to the markets. This nanotechnology application is based on the coating of glass with TiO2 nanoparticles during the manufacturing process which has the functionality of breaking down organic dirt to subsequently be washed away by rain. However, the limited R&D resources that Pilkington Finland has imply that the role that it can take as an early user of nanotechnology applications in glass-processing is marginal. Further, the recent closure of the Lahti float-glass factory, which also acted as a pilot production plant, is bound to diminish the overall role of Pilkington Finland in the value chain.

While the glass-producing and -processing segment of the industry in Finland is dominated by Pilkington Finland, and the bulk of glass sheets for further processing in the construction industry originate abroad from the large multinational companies, there are numerous other smaller glass-processor and *sub-system assembler companies* the latter of which occupy the next segment of the value chain. These companies develop various joinery products based on pre-cut and processed glass sheets produced by the multinational companies. Of particular interest in the context of the construction industry are the window producers, represented here by Fenestra.

5.2.2 Fenestra Oy

This company is the leading window and door supplier in Finland with activities throughout the other Nordic and Baltic countries as well. It belongs to the Paloheimo family company founded in 1889. Today Fenestra employs some 1100 people with sales of approximately 150 million euro. Fenestra's business operations are divided into six different sectors: construction companies, high-rise renovation, house building factories, retailers, agents and export. The company has production plants in Finland at six different locations with sales offices in the vicinity of all major towns, the primary customers being DIY chains and construction companies.

As opposed to the dedicated nanotechnology companies and the glass-producers, such as Pilkington Finland, Fenestra more clearly represents a possible user of nanotechnology. In fact Fenestra has already been involved in the early application of Pilkington's Activ glass in 2002. Fenestra was among the first pilot customers for launching this nanotechnology enhanced product, along with some other companies in small countries such as Ireland and Austria. The initiative for this piloting came from the R&D unit of NSG/Pilkington in the UK, and it involved some vocational training, especially amongst sales personnel, as well as some reorganization of production lines. One challenge was to manage incompatibilities between the structures and materials used when framing glass into wooden elements and the nanoscale coatings used for the Activ glass. Even though Active glass provides a new and interesting business area for Fenestra the share of turnover of window elements that use this nanotechnology application is still very small. Nanotechnology-enhanced window elements are priced above the traditional ones and primarily attract a younger generation of private house builders.

Apart from piloting Activ glass Fenestra is also involved in some other nanotechnology-related R&D activities, mainly representing the user perspective. The in-house R&D activities of this company are fairly limited and R&D projects are typically outsourced to the VTT and university groups. One R&D project is underway to investigate the application of Sol-Gel techniques to protect the wooden window frames from adverse effects of moisture and rain. These activities have been part of the Tekes PINTA program and also introduce Fenestra to the smaller nanotechnology-dedicated companies in the field. Overall environmental concerns, related regulations and demand for eco-efficient construction sub-systems are the main drivers behind an interest in new technologies.

The final, downstream, segment of the central value chain is populated by the bigger *construction companies* as systems integrators which integrate various components, elements and services during on-site construction projects. Construction companies have to calculate the costs and benefits of the procurement and integration of new technologies over the total lifecycle of buildings, while also taking the needs of consumers (real estate owners) into account. They will thus play a key role in considerations of the cost-efficiency e.g. of new nanotechnology applications in the glass-processing industry. Some construction companies also provide real estate renovation, management and maintenance services and thereby take an interest in new technologies which increase functionality and productivity, a good example being various ICT solutions.

As in many other countries in Finland this segment of the value chain is dominated by a few larger companies, some of which are diversified multinationals. The main construction companies active in Finland include the Swedish owned multinationals Skanska and NCC as well as the Finnish companies Lemminkäinen and YIT. Skanska and NCC entered the market through acquiring Finnish companies in the aftermaths of the economic recession of the early 1990s that hit this industry especially hard. Thus, Lemminkäinen and YIT are the only large Finnish construction companies with activities of relevance to nanotechnology. YIT is here taken as an example of a technologically progressive company.

5.2.3 YIT Oy

YIT Oy was formed in 1987 through the fusion of three smaller companies in the industry. The company spans four major business areas, namely Building Systems, Construction, Services for Industry, Networks and IT. This relatively diversified structure enables the company to provide a broad range of products and services, ranging from the construction of new buildings, renovation, various utility installation services to maintenance and real estate ICT support services. The company employs some 25 000 people with a turnover in 2008 of 3.9 billion Euros, and thereby ranks among the largest companies in Finland. The main markets are in the Nordic and Baltic countries as well as in Russia.

YIT does not organize R&D activities centrally but engages in various development projects on a project basis. These projects are often involved in collaboration especially with the Technical Universities and the VTT. YIT Oy is also a frequent participant in technology programs commissioned by Tekes in which it represents the user perspective of new construction technologies and solutions. A major part of these projects relate to ICT and energy systems as means to increase productivity and achieve higher eco-efficiency of buildings.

The Construction business area of YIT is the one that primarily may benefit from nanotechnology developments. Nonetheless, although there is an interest in, and awareness of, nanotechnology developments, cost considerations have hence far worked against the introduction of new applications, such as self-cleaning windows. Apparently nanotechnology enhanced construction elements still have to prove their cost-efficiency and value proposition from the viewpoint of consumers of new buildings. However, in a longer term perspective concerns about productivity and eco-efficiency can pave the way for increasing uptake of nanotechnology applications. This could concern especially applications for reducing energy consumption in line with new regulations, as well as the use of ultra precision sensors to monitor maintenance needs of buildings.

Apart from this central value chain there are a couple of glass-processing machinery companies, illustrated in the upper part of figure 1 as constituting the *supporting and adjacent industries*. In addition a few dedicated nanotechnology companies are attempting to enter the value chain as suppliers of intermediary products and machinery, here best exemplified by *Beneq Oy* and *Millidyne Oy*. These companies can be classified as nanotechnology materials companies with R&D activities of potential relevance to a whole range of industries. The applications of most relevance to glass-processing and windows include machinery, equipment, and techniques for achieving self-cleaning new functionalities for windows; these applications represent competing alternatives to Activ glass originally developed by NSG/Pilkington.

Finally, the bottom part of the figure illustrates *public sector activities and actors* that constitute the institutional infrastructure of particular relevance for the application of nanotechnology in the Finnish glass-processing industry. As regards glass-processing machinery producers, Finland currently hosts a number of such machinery suppliers, perhaps the most well-known internationally being Tamglass Oy.

5.2.4 Beneq Oy

The first nanotechnology dedicated company Beneq Oy was founded in 2005 as a spin-off from Nextrom, a developer and supplier of machinery for the production of fibre optics for the global ICT industry. Beneq employs some 20 people with rapidly growing sales; the company received a growth-company award in 2008 for its achievements and it has also been considered as one of the 50 most promising cleantech companies in the Nordic market. Thus Beneq has, very quickly, managed to commercialize nanotechnologies successfully in their application niche. The personnel have a strong background in both business and R&D, primarily in applied physics.

Beneq Oy offers applications, related equipment and machinery based on two generic process technologies, namely Hot Aerosol Layering (nHALO) and Atomic Layer Deposition (ALD). nHALO is a flame spray technology used mainly for applying coatings on glass and ceramic tiles. These coatings add self-cleaning, colouring, solar control as well as antimicrobial functionalities to glass or ceramics either through the deposition of necessary nanosized particles on the surface or through the infusion of other types of substrates into the actual matrix of the material. Both of these technologies are sold through licensing, while Beneq also produces and sells ALD equipment.

The nHALO technology, of particular interest in this context, has its origin in research during the early 1990s in the field applied materials at the University of Art and Design in Helsinki, as well on aerosol physics at the Tampere University of Technology. Originally nHALO was commercialised through ABR Innova, a company founded in 1995 to develop photonics-related technologies that gradually shifted towards tailored colouring technologies for household and art glass. Through external ventures ABR Innova stimulated further entrepreneurship through the funding of the companies Liekki Oy, Fotonium Oy and Innolasi Oy as suppliers of related machinery and equipment. Meanwhile ABR Innova started to establish foreign sales offices and also extended R&D collaboration towards other universities and research institutes both in Finland and abroad. In 2005 ABR Innova was merged with Beneq Oy.

Beneq has mainly collaborated with the *Aerosol Physics Laboratory* at Tampere University of Technology, the *Process Chemistry Department at the Åbo Akademi University* and *Micronova*, and the company also participates in the Tekes FinNano programme.[52] Collaboration further downstream extends to subcontractors in the supporting and adjacent machinery end engineering industries.

Collaborative initiatives and discussions have been underway with various Finnish glass-producers and -processors. Still growth is foremost expected in foreign markets in which both the predecessors Nextrom and ABR Innova, as well as Beneq, have established sales offices and various partnerships.

5.2.5 Millidyne Oy

The second nanotechnology dedicated company, Millidyne Oy, was founded earlier in 1997. Millidyne specializes in various functional coatings for a broad range of materials, including glass and ceramics. This company employs around 10 people with sales of some 1 million based on information from 2006. The growth of this company has been moderate at an annual rate of some 20 percentage. Millidyne is a spin-off from the Tampere University of Technology, although it is partially owned by the pulp & paper machinery conglomerate Metso Oy. The idea behind the founding of this company relates to a collaborative R&D project tailored to specific needs of Metso, and this partnership has provided a good basis for the further diversification towards other industries and application areas.

Millidyne provides ceramic powders for thermal spraying, sol gel coating raw materials and speciality coating resins for various surface applications. Of these the sol-gel technologies are of particular interest for the glass-processing industry. Sol-gel technologies basically achieve some of the similar coating functionalities as flame spray technologies although it also, to a greater extent, involves wet chemistry. Sol-gels are suspensions contain-

[52] Micronova is an R&D centre for the design, development and fabrication of micro- and nanosystems, run jointly by the VTT Technical Research Centre of Finland and Helsinki University of Technology

ing nanoparticles for specific functionalities that can be gelled on the surface of the target material to form a solid coating. It is thus easy to process and apply. Millidyne sells these nanotechnology-enhanced sol-gels as tailored raw materials for specific applications.

Currently the sol-gels account for a lesser share of the turnover of this company, but a lot of business potential has been envisioned especially in the field of anti-bacterial glass and ceramics for the construction industry. Exports account for a significant share (30 percentages) in 2006, mainly related to corrosion protective coatings for the machinery and equipment industry through the partnership with Metso.

Various collaborative contacts have been developed with the research community in Finland, among others with the Ceramic materials and Surface engineering Laboratory at the Tampere University. Millidyne has also participated actively in relevant public R&D projects, including the Tekes PINTA and FinNano programs. Collaboration mainly covers material technology where attempts are made to diversify the use of sol-gel technologies for various different types of materials beyond metals as the first major application field. As suggested above, Millidyne is also actively probing different entry points into the glass-processing value chain in collaboration with glass processor, sub-system supplier, and construction maintenance companies in Finland and abroad.

5.2.6 Tamglass Oy

Tamglass Oy is part of the Glaston Corporation. Glaston Corporation was formed in the summer of 2007 to overtake all business activities of Kyro, the forerunner family corporation established in the late 19th century. Today Glaston Corporation is a major glass processor and machinery supplier for applications in the construction, automotive, and furniture industries worldwide.

Tamglass focuses on the development and production of safety glass in these application industries. Out of the total float glass production globally around 40 per cent is processed into safety glass. According to Glaston Corporation around one half of this has been processed using their machinery implying a global market share in this particular industry has been more than 50 per cent. This makes Tamglass a major player in the field, also internationally. In 2006 this company employed 600 people with manufacturing units in Finland, the US, Brazil and China. The R&D share of turnover is in the range of 3-4 percentages and most of this is still accounted for by units in Finland. Nonetheless, the current economic crises has also impacted this company and lead both to rationalizations of their machinery business as well as the divestment of the glass processing business which was overtaken in April 2009 by the German company Interpane AG.

Nanotechnology developments in the glass-processing industry are of direct interest to Tamglass as new types of functional coatings also eventually will require new types of machinery. The company takes a relatively active stance in monitoring nanotechnology developments, among other activities through the organisation of the biannual Glass Processing Days, an internationally recognised event in the industry. Further, some R&D projects have already been initiated with the dedicated nanotechnology companies that also involved research groups at universities and the VTT. One challenge in this segment of the value chain in Finland is the lack of glass-producing and -processing companies as lead users of new technologies, especially following the closure of the Pilkington Finland float glass factory in Finland.

5.3 Drivers for eco-innovation and the development of green nanotechnologies

According to the case study interviews the growing demand for eco-efficient buildings to mitigate climate change has been the main driver for eco-innovation in this industry. Nanotechnology can improve the eco-efficiency of buildings through many routes of which the nanotechnology applications being developed in Finland constitute good examples. This growing demand primarily relates to global norms and regulations which have subsequently also been incorporated in Finnish legislation. Even though most of environmental legislation has been harmonised with EU legislation already in the 1990s, two acts should be highlighted in this context. The 2000 Land Use and Building Act provided municipalities with a higher degree of autonomy in local land use planning enhanced participation of stakeholders in various planning phases and introduced provisions to prevent pollution. Further, the Energy Certification of Buildings Act came into force in 2008 based on the EU Directive on the Energy Performance of Buildings, clarifying eco-efficiency norms in construction further.

Apart from eco-efficiency considerations and regulations, the availability of relevant machinery and instrumentation as well as technology programmes have also played an important role in promoting R&D and innovation in green nanotechnologies even though they have not focused on eco-innovation per se. The Tekes PINTA (Clean Surfaces) programme during 2002-2005 appears to have had a particularly important role in influencing and directing some R&D projects towards eco-efficient nanotechnologies, and it has also contributed to increasing collaboration and coherence throughout the R&D community in the field. The PINTA programme investigated the usability of functional coatings on many different types of materials but put particular emphasis on atomic layer deposition (ALD) and sol-gel technologies that are now the two main R&D paths that are being followed for applications in glass-processing and windows. Some R&D projects continued in the FinNano programme and may receive further funding through new Tekes programme named Functional Materials established in 2007.

Even though the public R&D programs have been important some concern was also raised that applications in high-technology industries have been prioritised too much and at the cost of many promising areas in the more traditional industries such as construction. One reason for this may be that natural scientist, especially in the field of physics, often are preoccupied with applications in the electronics industry, while they are less alert on opportunities outside ‘high tech’ areas. Further, the cross-over between nano- and biotechnology has been excluded from Tekes FinNano programme with inhibiting effects on diversification towards e.g. bioactive glass and other new and interesting areas of relevance to eco-efficiency.

5.4 Facilitating and inhibiting factors in commercialisation and industrial uptake

There is already a well-established, but small, community of researchers within this field in Finland. This community has developed a relatively clear division of labour with activities covering the basic characterisation of ceramic and glass surfaces, the application and measurement of nanotechnology coatings, as well as the development of some of the related machinery, and the pilot scaling of these processes for industrial production. As indicated, the nanotechnology-dedicated companies Beneq Oy and Millidyne Oy are also quite active in this community. The first phases in the development of ALD and sol-gel technologies – as the main technologies in Finland which are applicable to glass-processing and windows – have benefited from the involvement of large and established companies as early users and providers of test markets. As these technologies have been developed further towards applications in the construction industry the involvement also of glass-producers and processors, as well as construction companies would be necessary to manage the transition from pilot to industrial level as well as to develop business models, retail and marketing capabilities.

The lack of involvement of large and incumbent companies as possible user of nanotechnology in the glass-processing, windows and construction industries is, to a large extent, an inherent feature of the structure and nature of these industries in Finland. The glass-producing segment of the value chain, as the most obvious entry point for new nanotechnology dedicated companies, is highly concentrated and dominated by a few multinational companies that master the prevailing and capital intensive float-glass process. This is especially the case in Finland where the only float-glass factory has been owned by the multination NSG/Pilkington with main R&D activities in the UK; as noted this only factory has subsequently (in June 2009) been closed down thus complicating the situation further.

The availability only of a few companies in the glass-producing and –processing segment of the value chain that could become users of nanotechnology inhibits entrepreneurial experimentation amongst possible users of eco-efficient nanotechnologies. There is less scope for product experimentation and validation as in order to achieve industrial-scale production and commercial breakthroughs. This same problem – the existence only of a few dominating companies which are reluctant to become involved in nanotechnology at this stage – complicates entry further downstream in the construction company segment of the value chain. Meanwhile it seems that the companies populating the intermediate and more fragmented glass-processor and sub system assembler segments of the value chain lack in-house R&D resources and risk-taking capability to become early users of eco-efficient nanotechnologies. The challenge is accentuated by the very different nature of the knowledge base of science-based nanotechnology compared with that of traditional glass-processing and construction industries in which technology change is slow and foremost incremental; it may be particularly hard to develop relevant absorptive capability to incorporate nanotechnology in these circumstances.

The apparent reluctance of especially the construction companies to become fully involved in nanotechnology at this stage is primarily due to the unclear value proposition of some of these new applications. These companies, which eventually procure and integrate various construction elements and sub-systems, have to engage in detailed cost-benefit analysis that cover the whole life cycle of a new building before they can make investment decisions related to specific construction projects. Even though nanotechnology-enhanced functional coatings can add value to glass, the higher price of these coatings can be hard to transfer to consumers as long as the benefits of nanotechnology are not yet obvious and clearly superior when compared with existing applications. Even though many interviewees did identify eco-efficiency as a major driver for becoming engaged in the field, it seems that the communication of the potential environmental benefits, as well as possible health and security risks, would require more and coordinated efforts that could also involve industry associations, architects, civil engineers and other relevant stakeholders. The market for green nanotechnologies would need to be legitimated further for larger scale industrial uptake and commercialisation to occur.

Some concern was also raised about the lack of specialized expertise in the application of nanotechnology in the glass processing industry. The interdisciplinary nature of this field implies that physicists, chemists, engineers, architects, designers and civil engineers have to work together. The knowledge base has to be quite large and diversified, and the importance of gate-keepers, which are able to integrate different disciplines for industrial applications, becomes pronounced. Finally, some specific and expensive research instrumentation is lacking, the access to which depends on international R&D collaboration. However, by and large resource mobilisation does not appear to be a significant inhibiting factor in this context.

6 A window of opportunity: the case of a materials venture in Sweden

6.1 Introduction

The time lags between invention and innovation, as well as between innovation and rapid market diffusion, are often long, taking decades rather than years (Grumbler 1996). Maine and Garnsey (2006) suggest that commercialisation of advanced materials technology meets specific challenges due to its generic and radical character and its upstream position in value chains. This creates a sustained high technological risk and a high market risk. The matching process between technological capabilities and demands in a specific market is difficult for technologies that are based on new scientific knowledge and can be applied in many different applications. Maine and Garnsey stress the importance of getting access not only to financing and but also complementary assets such as manufacturing expertise. They propose that advanced materials ventures are most likely to succeed if they develop IP claims on a long-term, emerging market application with major potential while focusing time and resources on substitution applications that can be realized in the shorter term.

To better understand the prerequisites for commercialisation of advanced materials technology we need case descriptions of success stories and failures. (Due to the time lags, one should however be careful when classifying a technology as a failure or success; what seems to be a failure may very well prove to be the success of a coming decade, and vice versa, a temporary success may fail in the longer term.) In this paper we will use the story of a materials venture in Sweden producing an electrocromic foil that can be used to construct what has been called ‘smart windows’, that is windows with a transparency to light that can be controlled by an electric field. The case illustrates the vulnerability to technological risks and market risks, the struggle of getting finance and complementary assets and the problem of approaching an established industry, such as the construction industry and the uncertainties related to the problem of selecting the best entry point in different value chains. Not surprisingly, we find that in the lack of existing industrial interest and capabilities the scientists cannot only devote themselves to narrow technical development but also need to broaden their scope and become a kind of system builders. The case illustrates the need for combining bold long term goals with a continuous effort to find short term next steps. It also shows that success is only partially governed by internal strategy and that the timing of internal effort with external society wide processes is of crucial importance. Finally it once again demonstrates the time lags involved in the commercialisation of scientific discoveries and hence has relevance for the ongoing debate on how investments in science are made useful for society.

6.2 Theoretical starting points

Technical change comes as a result of an intricate interplay between the creation of new technical opportunities and the creation and discovery of problems that needs to be solved. Here we will make no argument about what comes first, technology push or demand pull, but acknowledge that there is much feedback between the two, that opportunities may stimulate demand as well as demand may stimulate the creation of new opportunities. At the micro level, such positive feedback (or positive return) can generate an autocatalytic process (Marshall 1890; David 1985; Arthur 1988). This makes the development of specific artefacts highly unpredictable. However, there are also megatrends that set the scene for changes at the micro level that on shorter time scales can be viewed as given and beyond influence of any feedback.[53] From the opportunity (technology push) side, the accumulation of scientific and technical knowledge in society due to several hundred years of time devoted to scientific study and discovery and technical experimentation, involving a growing number of people, increases the knowledge base of society. New ‘design spaces’ are opened (Stankiewicz 2000). On the demand side, the escalating number of people and volume of consumption in a world with a limited physical resource base partly upheld by sensitive ecological systems creates a continuously increasing demand for more efficient and environmentally benign technologies. These megatrends of capabilities and demands form only part of the background to new ventures. We also need to consider that the uptake of new solutions is modulated by the existing industrial structure. A new solution may be more or less compatible with existing artefacts, competences, business models and user practices (Abernathy and Clark 1985; Kemp et al. 1998). To materialise, it needs to fit into existing value chains or have the power to change them.[54] These two levels, the mega trend level and the structure of the incumbent industry, are captured in the so called multi-level approach to technological transitions by the terms landscape and regime level, respectively (Rip and Kemp 1998; Geels 2004). The three-level model is completed by a niche level where novelties emerge.

To describe the prerequisites for success at the micro level (niche level) in more detail one can make use of the technological innovation systems (TIS) approach (Bergek et al. 2008a). A core idea in the model is that prerequisites for change can be analysed by a set of innovation system functions that describe the build-up of system components, such as actors, networks, artefacts, knowledge, regulations and attitudes (Bergek et al. 2008b). These functions provide a causal link between the preceding development within the system itself (endogenous forces) and forces that cannot be influenced directly by actors within the system (exogenous forces), e.g. broad societal trends or strategic behaviour of large incumbent firms. The combined effect of internal and external force fields creates a room to manoeuvre for system actors (e.g. entrepreneurs). While the TIS model mainly has been used to describe larger systems involving many actors, Hellsmark and Jacobsson (2009) use this framework to describe the role of a system builder coming from academia. In a similar way we here discuss how the prerequisites for success of a materials venture based on academic research depends on the changing strength of a couple of system functions over time due to the combined effect of internal accumulation of experience and external trends. While many functions has been suggested in the literature,[55] we here concentrate on knowledge accumulation and the role of external trends for the creation of legitimacy (such as the changing tides of environmental concern) that in turn guide direction of search and resource mobilisation.

6.3 Setting the scene: Swedish background trends and structures

6.3.1 The Swedish technology base: a growing stock of knowledge in physics based materials science

At the mega trend scale there has been a continuous accumulation of knowledge about the properties of matter over the last centuries. Over the last four decades there has been a growing interest in advanced materials science relative to other scientific fields. In Sweden, this comes out clear from bibliometric data. Figure 6.1 shows that the relative number of publications from scientists with Swedish affiliation within the combined subject areas ‘multidisciplinary materials science’ and ‘solid state physics’ in Science Citation Index almost tripled between 1973 and 2008. This mustering of strength in advanced materials science has opened new designs spaces and will likely offer a host of new solutions to problems over the next couple of years.

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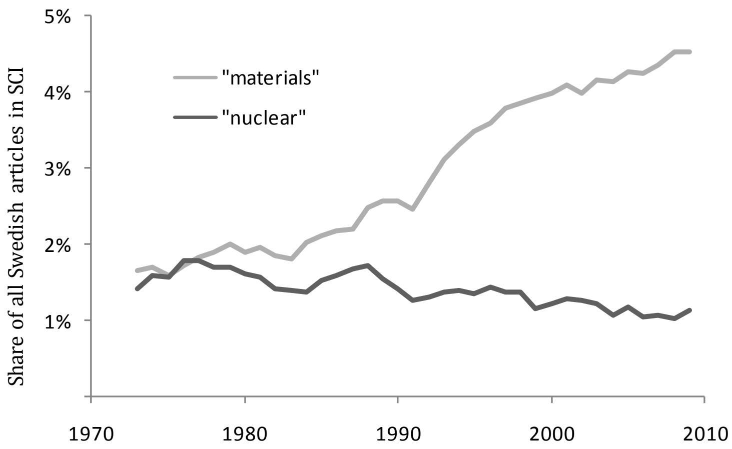
[53] Not to say that these megatrends are not part of grand feedback cycles, see for example (Diamond 1998).

[54] These two levels, the mega trend level and the structure of the incumbent industry, are captured in the so called multi-level approach to technological transitions by the terms landscape and regime level, respectively (Rip and Kemp 1998; Geels 2004). The model is completed by a niche level where novelties emerge.

[55] Bergek et al. (2008b) suggest a list of eight functions including knowledge formation, entrepreneurial experimentation (practical knowledge formation), legitimacy formation (providing the institutional back up in terms of regulations and attitudes), guiding the direction of search (lead to more actors - developers), resource mobilisation (financial resources and labour), market formation (customer mobilisation), materialisation (provide the material infrastructure) and development of positive externalities (free utilities).

Figure 6.1 Material science in Swedish academic publications

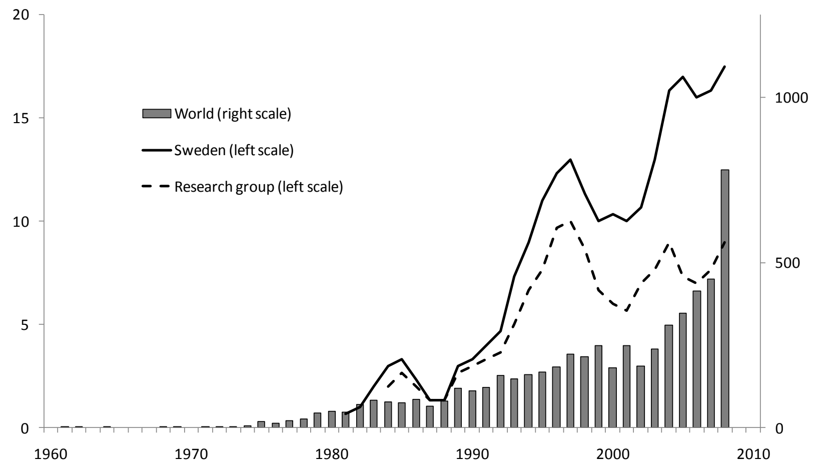


Source: Own source. Materials science is approximated by two subject areas (Materials science, multidisciplinary OR Physics, condensed matter) in Science Citation Index. The trend for two combined subject areas (Physics, nuclear OR Nuclear technology) representing another physics based area is included for comparison. The graphs represent three-year moving averages.

The development of electrochromic materials is part of this process.[56] Electrochromic materials are materials that change their optical properties when exposed to an electric field. Observations of electrochromic were made in the first half of the 20th century but more intense scientific inquiry did not start until the 1970's (Granqvist 1995). The bar diagram in Figure 6.2 illustrates the increase of academic publications on electrochromism in the world. In Sweden, the publication rate on electrochromism has been higher than the world average since the mid 1980s given that on average about 1.6% of all publications in the Scopus database have authors with Swedish affiliation (Figure 6.2).

Figure 6.2 The number of scientific articles on electrochromic

[56] Material that change their optical properties due to different stimuli are said to be 'chromogenic' (Lampert and Granqvist 1990). This group includes materials that are photochromic, thermochromic, gasochromic and electrochromic, that respond to light, temperature, gas concentrations and electric fields, respectively.



Source: Own source. The number of scientific articles (in English) on the topic “electrochromic*” in Scopus (three-year moving average). The bars illustrate the growth of worldwide publication on the topic (right scale). The line gives the publications from authors with Swedish affiliation and the dotted line the publications from the research group behind Chromogenics (professors Granqvist and Niklasson and the Ångström lab). Given that on average about 1.6% of all publications in the Scopus database have authors with Swedish affiliation, Swedish universities and in particular the research group in focus have had a strong position with regards to publications (the scales are adjusted to illustrate this relationship).

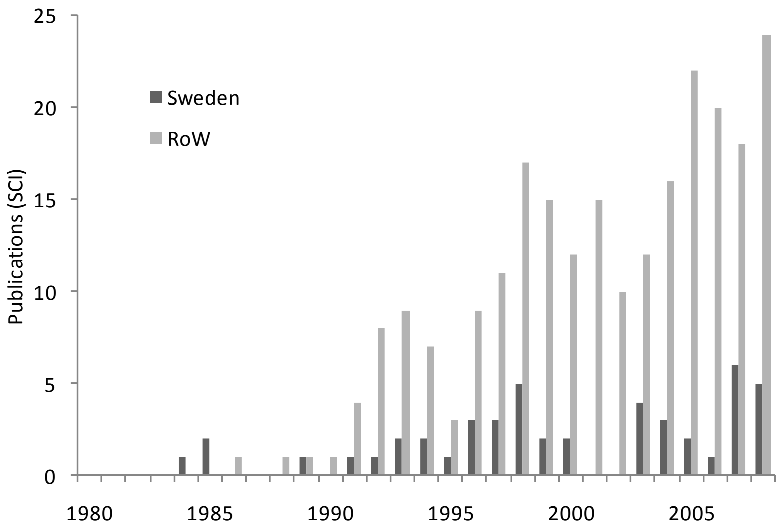
Electrochromic materials have many potential applications (Granqvist 2006). They can be used in energy efficient information displays. They require energy only when switching from one message to another. A second application is self-dimming rear-view mirrors in cars. A major potential application is ‘smart windows’ that can shift between a fully transparent and a dark state. Smart windows can in turn be used is a range of artefacts from ski goggles and motor cycle helmet visors to cars and buildings. In cars and buildings, they can be applied to increase comfort and save energy by controlling the inflow of light and heat.

The first three publications in Science Citation Index using the term ‘smart windows’ from 1984 and 1985 are published by two Swedish scientists (see below). The term was soon adopted by the international community and the annual number of publications on smart windows is increasing (Figure 6.3).[57]

In a recent review, Baetens et al. (2009) find that in 2009 three companies manufactured electrochromic glass that can be applied for outdoor building glazing: SAGE Electrochromics (USA), EControl-Glas (Germany) and Gesimat (Germany). Three more companies, Saint Gobain Sekurit (France), Gentex (USA) and Chromogenics (Sweden) produce electrochromic glass on a small scale for other applications, such as sunroofs and rear view mirrors in cars and motorcycle helmet visors.

[57] Compared to Sweden, the volume of publications on electrochromism and smart windows in the other Nordic countries is very small.

Figure 6.3 Scientific publications on smart windows



Source: Own source. Following three seminal papers by professor Granqvist and colleagues in the beginning of the 1980s, the number of annual international scientific publications on 'smart windows' started to grow around 1990 and has continued to do so over the last two decades (search term TS=(smart window or smart windows) in Science Citation Index).

6.3.2 Changing demands: the tides of environmental concern

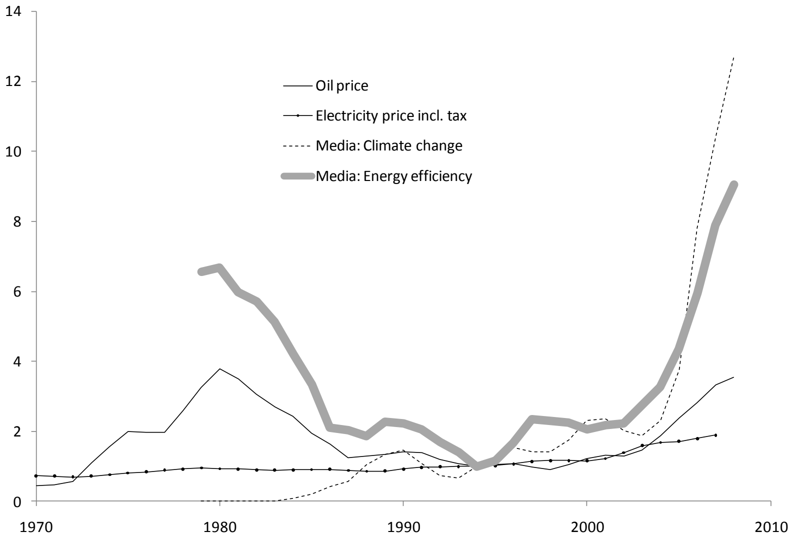
The major driver for interest in smart windows in buildings and vehicles is the increasing demand for energy efficient solutions that at the same time preserve or increase the level of comfort.

It is difficult to estimate potential energy savings from usage of smart windows, but computer simulations indicate that energy for cooling and lighting may be reduced by 10-40% compared to low emitting glass in commercial buildings in a broad range of climatic zones (Lee et al. 2004; Ramezani and Nybom 2009). A 20% reduction of electricity for cooling could correspond to some 3% of electricity consumption in industrialised countries.[58] Smart windows could also reduce peak demand of electricity for cooling which may lower the required capacity of air-conditioning installations and, at some locations, peak power production capacity in the grid. Further, smart windows will most likely co-evolve with other changes in building materials and architecture which could result in larger gains in system efficiency. Also lowered savings due to rebound effects are imaginable (e.g. if the adoption of smart windows stimulate a continued development towards larger glazed surfaces).

While striving for various types of energy efficiency has been a driver for technical change since the dawn of humankind, the intensity of this force fluctuate over shorter time intervals. Figure 4, based on Swedish data, reveals a U-shaped pattern over the last three decades. The fat grey line shows the number of articles in non-academic press (newspapers and magazines) on energy efficiency. From high levels in the 1970s, the interest declines in the 1980s and remains low over a fifteen year period until after 2000 when a new wave of interest takes publication rates to a new high. In the figure, three possible underlying causes are illustrated: the ups and downs of the international oil price that drove the interest in the 70s and contributes in last wave, the steadily increasing real electricity price and the exploding interest in climate change after 2003.

[58] Based on the assumption that 15% of electricity consumption is used for air-conditioning.

Figure 6.4 Non-academic publications on energy efficiency in buildings



Source: Own source. The high interest in energy efficiency in buildings in the 1970s, indicated by articles in news papers and non-academic magazines, eroded to recover only after 2000. Three underlying trends that might explain the shifts are shown in the figure. The real oil price followed a similar curve (BP 2009). The media coverage (Swedish newspapers) of climate change increased dramatically after 2003. The real electricity price for private consumers increased continuously over the entire period, but somewhat faster after 2000 (nominal values from Swedish Energy Agency (2008) deflated by the consumer price index). All curves are three-year moving averages normalised by 1994 values to show relative trends. Interest in energy efficiency is measured as hits in the Swedish database Artikelsök, search term (”Energiförbrukning"/äo ELLER "Energihushållning"/äo ELLER "Energihus"/äo ELLER "Energieffektivisering"/äo ELLER "Energisparande"/äo INTE "Industriell energiförbrukning"/äo INTE "medicin"/äo INTE "Livsmedel"/äo INTE "Kärnkraft"/äo). Search term for climate change: (koldioxid* ELLER klimatförändring* ELLER drivhuseffekten ELLER växthuseffekt*).

Even if the major markets of smart windows lie outside of Sweden and Scandinavia, these trends are likely to influence the direction of search of researchers and investors alike towards all kinds of technologies that target energy efficiency as a primary performance criterion.

6.3.3 The industrial structure: The glass value chains[59]

The two major potential application areas of smart windows are buildings and vehicles. The electrochromic material needs to enter the value chains of construction and automotive glass at some point. The structure of these value chains and the type of firms populating them will affect if and how a new technology will be adopted.

The main type of glass used for construction is manufactured through the so called float process, invented by Sir Alastair Pilkington in 1952. Today, the global glass industry is mature and concentrated. It is dominated by four companies -- Pilkington/NSG, Saint-Gobain, Guardian and Asahi Glass (AGC) -- which together account for 66 percent of the world market and 82 percent of the European production capacity. Excluding sales offices and distributors, only Pilkington and Saint-Gobain have activities in Sweden. Neither of the companies performs any R&D in Sweden. Pilkington/NSG has one float glass plant in Sweden (out of about fifty globally) and one plant that produce automotive glass.

Glass may be processed off-line, that is after the glass has been produced. Few companies handle only this part of the value chain. Such processing is often done by either the glass manufacturers themselves, or by the manufacturers insulating glazing units (IGUs) and windows. The activities of Saint-Gobain are limited to glass processing and IGU manufacturing. In comparison to float glass manufacturing, there are many companies that take regular or processed float glass to produce IGUs and windows for building. A search in the online version of the yellow pages (www.eniro.se) gave 357 companies with the keyword "window manufacturing" (Swedish: "fönstertillverkning").

The Swedish construction sector has four large companies of dominating size, but there are also hundreds of smaller contractors. The construction industry is often described as being "traditional" or "old-fashioned", with comparatively little R&D activity. Even if the construction companies are not active in researching to create innovations, they "innovate" every day by solving problems in the different building projects (Skarendahl 2008). The problem with this approach might be that each project becomes a restart for innovation and that the organisational learning is thus low. The representative of the Swedish Construction Sector Innovation Centre (BIC) estimated that very few small companies are active in product innovation (Skarendahl 2008). Unlike the automotive industry, none of the large construction companies have venture capital firms that invest in emerging technologies (Carlen-Johansson and Nordberg 2009, Alvesjö 2009). The automotive industry in Sweden consists of a few car and truck companies (at the time of writing two truck companies and two car companies). These companies cooperate with original equipment manufacturers in development projects and Volvo Technology Transfer is a venture capital firms that invest in new technology that is of potential interest to the automotive industry.

There are also substantial after sales markets for construction and automotive glass. There are numerous glaziers that and retailers in these markets. A search on the Swedish yellow pages for "glaziers" (Swedish: "glasmästerier") resulted in 1336 hits out of which 834 are in the category with the same name.

6.4 The story of a materials venture

The story of a materials venture around attempts to make a business out of knowledge generated in research on electrochromics is divided into two parts. First the recent fairly strait forward and successful development is described, and then the twists and turns in the preceding period are brought into the light.

6.4.1 The period 2003-2009: A clear view

In May 2002, a group of researchers from Uppsala University under the name of ChromoGenics was among the winning teams of Venture Cup, a business plan competition for university spin-offs. They were awarded 50 000 SEK (5000 Euro). The first of January 2003 the private limited company ChromoGenics Sweden AB was constituted (in 2008 renamed ChromoGenics AB). The core idea of ChromoGenics was to make an electrochromic foil

[59] The author is thankful to Kristian Jelse who provided valuable input to this section.

that can be applied to control transmittance of light at different types of transparent surfaces from helmet visors to windows in cars and buildings. It can also be used for energy efficient displays. The company was built on knowledge generated from 20 years of research on electrochromic materials at Chalmers University of Technology and Uppsala University by professor Claes-Göran Granqvist and colleagues.

From 2003 to 2009 ChromoGenics received a large number of awards and entered many top lists of ‘the most promising...’ spin-off and clean tech companies. According to Global Cleantech 100 set up by The Guardian and Cleantech Group, ChromoGenics was among the hundred most promising private clean tech companies in the world in 2009.

The first product segment that was aimed at was eyewear including solutions for motor cycle helmet visors and ski goggles. In 2004, the company had established relationships with leading producers of helmets and sports equipment.

In 2005, Volvo Technology Transfer, DuPont and two local innovation support organisation (Uppsala University Holding and Innovationsbron) invested approximately Euro 2 million to start up production. This investment did not only provide resources but also legitimacy, which in turn attracted more capital (Granqvist 2009). In addition, Uppsala University Holding provided support related to patenting.

A batch process for foil production was built up and in November 2009 the company made the first delivery to costumer of electrochromic foil for helmet visors (Almesjö 2009). However, it was not mainly for high tech ski goggles and helmet visors that Chromogenics received awards and attracted investors. The communication that the electrochromic foil would be ideal for production of smart windows for cars and buildings with potential huge markets was of greater importance attract attention (Almesjö 2009). Since the eyewear niche markets will be supplied by foil from a high cost batch process, they are unlikely to in themselves generate the revenues needed to go to the larger scale low cost roll-to-roll process that is required for the smart window markets. Nevertheless, the eyewear niche markets add three important things to the company (Almesjö 2009): First, they constitute a convincing demonstration of the viability of the technology. This is of critical importance for investors and potential industrial partners. Second, many of the numerous bugs that always show up in new production systems can be fixed in a small but real production setting. This experimentation leads to the development of crucial practical and tacit knowledge. Third, starting production for commercial markets at a small scale enables the company to initiate the transformation from an R&D organisation to a business oriented company.

In this way Chromogenics were doing exactly what Maine and Garnsey (2006) suggest that advanced materials ventures should do to succeed: develop IP claims on a long-term, emerging market application with major potential while focusing time and resources on substitution applications that can be realized in the shorter term.

The choice of producing a plastic foil instead of developing a process for making electrochromic thin film on glass as their competitors did opened a path towards lower costs and reduced problems with shortcuts. In addition, the flexibility of a foil increased the opportunities to enter different niche markets. The foil can be attached to different types of surfaces, not only glass, which extends the range of applications. The foil technology also creates a business advantage when approaching the window value chain. The large float glass manufacturers such as Pilkington and Saint Gobain have made attempts to develop electrochromic glass themselves and run minor production lines. They have the technical expertise that would enable cooperation but they are also competitors with great strength and hence a threat to the small start-up company. However, the add-on character of the foil enables direct cooperation with actors further down the value chain, i.e. window manufacturers and car companies. These are closer to end users and see market opportunities glass producers are not aware of (Almesjö 2009). One challenge for this strategy has been to bridge the gap between the science-oriented company and the more practically oriented window manufacturers (Granqvist 2009). The Swedish window production segment is characterised by many small companies (Section 6.3.3). However, some window manufacturers in Sweden and other countries are more advanced than others and a more close cooperation is about to start with one or a few window manufacturers (Almesjö 2009). At a later stage the foil technology will also make it possible to enter the market for widow refurbishment, i.e. it can be attached to old glass panes.

So far, this appears to be a story of a ‘by the book’ development. Even though the company still doesn’t generate revenues, there is a clear view of how to seize the business opportunities of the technology. To clarify some aspects of the prerequisites for this success we need to go back in history and take a look at the first two decades of development.

6.4.2 The period 1974-2002: Opaque dreams

Coming back from a post-doc visit at Cornell in the US, Claes-Göran Granqvist started research on coatings for solar heating panels at Chalmers University of Technology in Göteborg in the mid 1970s. He was inspired by the pioneering research on nanoparticles conducted at the American lab he had visited and was pulled towards energy applications by the oil crises and the lively societal debate on alternative energy sources (Granqvist 2009). The societal concern for energy issues also mobilised resources in terms of research funding. The research was diversified into studies of controlled cooling of surfaces by the use of thin films on glass. Some thin films deposited on glass change the absorption, reflectance and transmittance of light and heat radiation. This effect can be used to avoid frost on car windows but it can also be used to create surfaces that are cooler than the surrounding air. Based on this research, Granqvist and colleagues formed his first company ‘Radicool’ in the early 1980s, with wild ideas of how to irrigate desert areas with condensed water. The company mainly came to do consultancy work within the field of thin films and coatings. This lead led to new ideas of how to control transmittance of heat and light through windows.

Much helped by a co-operation with Carl Lampert in the US and Jim Stevens in Canada, Granqvist and a PhD student started research on ‘smart windows’, a term coined in their first publications on the matter in 1984 and 1985 (Svensson and Granqvist 1984a; Svensson and Granqvist 1984b; Svensson and Granqvist 1985). Initially, they also studied thermochromic and photochromic materials, but came to the conclusion that electrochromic materials were most promising. During the 1980s the group around Granqvist published several papers on electrochromic materials and smart windows (Figure 2). With his interest in energy issues, Granqvist saw the great potential of this technology and in 1986, together with the former PhD student Tord Eriksson, he formed Coat AB, a spin-off company with the explicit aim of commercializing coating technology in general and smart windows in particular (Lindholm Dahlstrand 1992). They realized that they had limited resources to develop the technology on their own, and that they had to co-operate with an established industrial actor. They considered manufacturers of coating machines, glass manufacturers and large users of coated glass, such as construction companies or car manufacturers. In, 1986, they established a relationship with the German machine manufacturer Leybold. They also needed capital to develop their own part of the business and it took until 1989 before they had secured the financial support from the University and a group of organizations providing seed money to start ups. While smart windows where considered to be the main product, due to the generic character of the core competence, a number of other diverse applications where investigated, from coatings in medical applications that reduce risks of infection to camouflage foil for the army. However, in the end, the company mainly generated incomes from consultancy work.

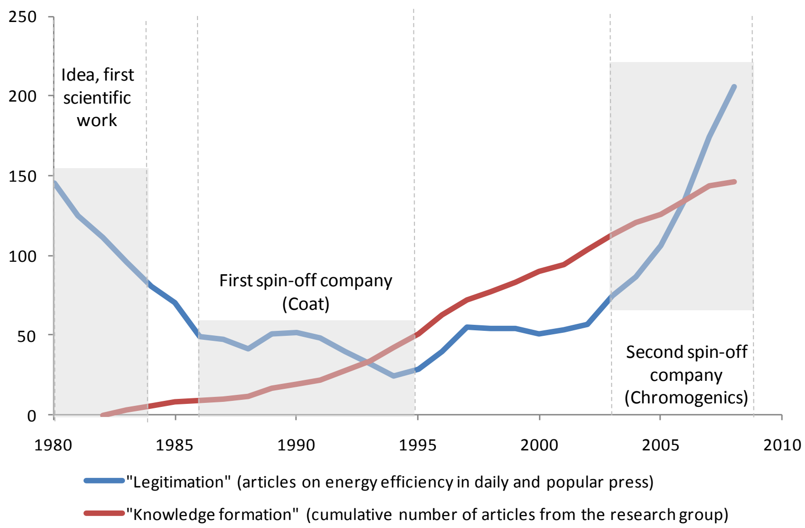
In 1988 and 1989, Coat and smart windows got publicity. The company won a national innovation competition (Innovation Cup), they were first page news in Financial Times and Tord Eriksson was interviewed in Australian television (Eriksson 2009). When asked by an American investment bank on when they were going to have a commercial product Eriksson said: “within two years”, and the investment banker was very disappointed with the long time horizon (and as we have seen it did not take two years but two decades).

In 1990, Leybold was bought by the large chemical company Degussa. Due to the ongoing recession, many developing project was shut down, one of them being the cooperation with Coat. Suddenly it was difficult to find partners and funding. Contracted people had to leave the company. As is evident from Figure 4, the interest in energy efficiency had eroded after the collapse of the oil price in the mid 1980s and through the spread of neoliberal ideology and the emergence of a financial crisis that put short-term costs cutting in focus throughout the economy. Coat stayed afloat with soft money from the EU. A prototype was sold to Volvo to make an inroad into the car segment (Lindholm Dahlstrand 1992), but it was not put into use. An attempt was made to approach the float glass manufacturer Pilkington (Eriksson 2009). Pilkington made tests to compare Coat’s technology for smart windows with the technology they had developed in-house. In 1995, Pilkington decided to continue development of their in-house technology and rejected Coat.

While commercialization of smart windows within the firm Coat AB had reached a stalemate, research on electrochromic materials took a new turn. In 1993, Granqvist considered an offer from a German University but eventually got a professorship at Uppsala University. In 1995, the research group moved to the newly built Ångström Laboratories. Together with two groups developing thin film solar cells, the smart window group formed Ångström Solar Centre that got funding from Mistra and the Swedish Energy Agency to go from research to applications. The group expanded and publications accumulated. However, the funders and management of Ångström solar centre gave most attention to solar cell development and Granqvist left the program in disappointment. In 2004, there was little or no money available for research on smart windows in Sweden and the established group with accumulated knowledge from two decades of research and experimentation was on the verge of collapse (Granqvist 2009).

Now it was time for the commercial side to take over the lead again. An idea of a new product had been growing for a couple of years. It started around 2000, when a physics student asked if electrochromic materials could be used for switchable visors for motor cycle helmets. It led to a master thesis (Gustavsson 2001) and academic papers (e.g. Azens et al. 2003) on the topic of electrochromic polymer foils for use in e.g. visors and a decision to join the competition Venture Cup in 2001. In 2002, they won Venture Cup and in 2003 the Company ChromoGenics was formed. A local innovation support organisation (Innovationsbron) that had been involved in Ångström Solar Center saw the potential and together with the holding company of Uppsala University they stepped in at a critical moment. An experienced chairman was contracted and he gave the company legitimacy in non-academic circles. At the societal arena, the pendulum once again moved towards greater interest in energy efficiency (Figure 6.4). The oil price was going up again, electricity prices had grown continuously for many years and most importantly climate change was rapidly gaining momentum as a major global issue. The future was suddenly brighter.

Figure 6.5 Development over time in company and societal interests



Source: Own source

In a first period the scientists were guided towards the area due to broad societal concerns over energy issues. The first spin-off company (Coat AB) was created at a time when the knowledge base (measured as cumulative number of articles from the research groups, see Figure 2) was limited and the societal interest in energy efficiency was decreasing (measured as articles on energy efficiency in daily and popular press, see Figure 6.4). When the second company (ChromoGenics AB) was formed, the knowledge base had increased substantially and the societal interest in energy efficiency was high once again.

6.5 Conclusions

In a first early phase, direction of search of the key researcher was guided by an awareness of new technical opportunities derived from a visit in the US and an interest in proving energy efficient solutions derived from the societal debates on energy and environmental issues during the 1970s and early 1980s (Figure 6.5). Fundamental knowledge formation started with important contributions from the international research community. In a second phase, a first spin off company (Coat AB) was formed. The invention of the concept “smart window” attracted much attention but Coat tried to commercialise the technology at a point in time when the in-house competence was still limited and the direction of search among potential investors and industrial partners where not any longer guided towards energy efficiency. The strong legitimacy for investing in energy efficient technology with long payback times was fading (Figure 6.5). In addition there were no short-term markets in sight that could have attracted investors for other reasons and enabled a development of practical experience and business competence. Instead most work went into creating a product for the potentially very large smart window markets. In this phase there was still not enough endogenous strength within the company and the exogenous forces conspired against an engagement of strong actors with complementary assets.

The technical knowledge base continued to increase due to the accumulation of academic work. The earlier experience of entrepreneurial experimentation enabled the research group to pick up an idea from a student of using electrochromics not for windows but for helmet visors and producing an electrochromic foil instead of techniques for depositing thin film on glass. This constituted the core business idea of the second spin-off company, ChromoGenics AB, which was formed in 2003. The in-house competence was now much larger after two decades of research and experimentation. The combination of short-term niche markets and visions of long-term grand markets was attractive to investors. They were doing what Maine and Garnsey (2006) suggest that advanced materials ventures should do to succeed: develop IP claims on a long-term, emerging market application with major potential while focusing time and resources on substitution applications that can be realised in the shorter term.

The first investors increased the legitimacy that enabled others to follow. One should notice that a Volvo company was one of the first investors and that the technology was not new to them but had been tested ten years earlier. The strong academic reputation of the research group probably also contributed to legitimising the technology. Professor Granqvist is the researcher with most publications in the field in the world. The conceptualisation of the technology as “smart windows” was likely also a contributing factor to positive attention. It has attracted media coverage since the 1980s.

Notwithstanding the importance of the endogenous forces created from the cumulative development around the technology, the research group and the spin-off companies, it is clear that the development of ChromoGenics was partly enabled by exogenous changes. The renewed interest in energy efficiency was the major driving force for investors as well as industrial partners in the window value chains (Figure 6.5),[60] i.e. increased legitimation for energy efficiency guided the direction of search and stimulated resource mobilisation. Further, the worldwide development within thin-film technology now made it possible to buy manufacturing equipment almost off the shelf, i.e. materialisation was enabled. Technical competencies mainly came from within , i.e. from the involved research group, but it is important to acknowledge that knowledge formation within the area was now a worldwide phenomenon and hence knowledge could also be gained from an international pool of publically available research results (Figures 6.2 and 6.3). In addition, the business competence that is required to make the transformation from an R&D organization to a business oriented company could in this later phase be collected from the

[60] However, one should not neglect the fun-factor, the drive for product differentiation and the marketing value of a radically new product (Almesjö 2009).

pool of competence that had developed around management of university high-tech spin-offs in related areas such as biotech.

This type of latter type of positive externality will probably be of great importance for the commercialisation of nanotechnology in general. This point at a potential role a pioneering company like ChromoGenics could have for other advanced materials ventures in a country like Sweden. The experience they collect and the inroads they manage to make into established industries, like the construction industry, will create a path that other companies may enter and travel at with less difficulty. However, these inroads have yet to be made.

In this context it is worth noting that the development of the electrochromic foil enables some flexibility of where to enter the value chains of established industries. This flexibility makes ChromoGenics somewhat independent of the large international glass manufacturers and they can form partnerships with many types of producers and users. An interesting finding when comparing the large system integrating companies in the construction and vehicle manufacturing industries, respectively, is that a vehicle manufacturer like Volvo has a venture capital firm that invest in promising new technologies, such as ChromoGenics, while none of the large construction companies have. The construction companies wait and observe and expect that new solutions should be delivered through their materials suppliers (Carlen-Johansson and Nordberg 2009).

The eventual fate of electrochromic materials, smart windows and ChromoGenics AB is unknown and hide in the opaque future but the first thirty years of development demonstrate that opening a window of opportunity is hard work and takes many decades. However, when beneficial internal and external conditions coincide and complement each other, 'smart' entrepreneurs may connect the different elements into a 'configuration that works'.[61] The ongoing trends of development within nanotechnology and increased demand for environmentally friendly and efficient technologies set the scene for many new windows of opportunity to come. The accumulation of entrepreneurial journeys like the one described in this article will further fertilize the growing ground for new materials ventures.

[61] Concept suggested by Rip and Kemp (1998).

7 Conclusion and policy recommendations

This chapter first brings our analytical conclusions and succeeding presents our main policy recommendations.

7.1 The role of green nanotech in Nordic construction - an overall synthesis

Our overall analytical conclusions are summarized as follows:

1. The growing concern for the *environment has become one of the major drivers* for innovation in the construction industry as clearly illustrated in the three analyzed Nordic window chains. New profit opportunities are emerging as eco-innovation is no longer narrowly defined by compliance with current environmental regulation.

2. Our surveys and case studies indicate that the Nordic *knowledge base in the field of nanotechnology* with potential applications in construction has increased substantially during the last three decades. The growing knowledge base in the Nordic countries also implies a growing stock of competence (competent people). Although nanotech is still at a very early stage of development, the international development, more than the national or Nordic, has now created a situation where nanotech technical components and processing equipment can be bought off the shelf to complement components and processes developed locally. This enlarges the available design space and the possibility for industrial uptake.

3. However, *the uptake of nanotechnology* in the construction sector generally is still limited. The barriers to commercialization of nanotech are considerable in this early fluid stage of development where standards, capabilities and trust in the new technological field are lacking. Nanotech seems predominantly to be moving in the more high tech areas such as medico and ICT rather than in the direction of traditional sectors such as the construction sector. There is clearly a lot of unused nanotech potential in the construction sector if we compare our mapping surveys of potentialities undertaken and the actual activities in the case findings.

Specifically in the window chain the picture is more mixed; certainly the use of nanotechnology is advancing in the Nordic countries in recent years. We see several examples of nano-enabled product innovations along the window chain. Some have been there for a surprisingly long time, 20-30 years (the nano-coatings applied by the big glass manufacturers), while many of the other applications are of a recent date. Our findings confirm a very slow nano-commercialization process despite the huge investments into nanoscience internationally the last 15-20 years. E.g. the story of the Swedish company ChromoGenics demonstrates that it may take many decades for a new idea to go from lab to market penetration. Hence, some of the promising development projects reported on in our surveys will not have any economic or environmental impact for many years to come; others are already experiencing, or are close to, major commercial breakthroughs. We need, however, more in-depth studies to be able to estimate whether the use of nanotechnology is higher in the window chain than in the rest of the construction sector, but this may very well be the case giving the widespread use of nanotechnology among the big glass manufacturers. We have not been able to identify specific Nordic clusters or synergies as yet. The nano-activities in the window chains are quite different in the three countries. But more studies are needed in this little analyzed field.

4. The *structure of the window value chain* shows some pros and cons with regards to the uptake of nanotechnology. The interdisciplinary nature of the nanotech field implies that physicists, chemists, engineers, architects, designers and civil engineers have to work together. The situation in the window chain with a few very large technically advanced international glass manufacturers, many small mostly traditional glass processing and window manufacturers and a range of diverse cautious, project oriented construction companies create a difficult environment for new high tech materials ventures. Both incumbents, start-ups and the really big multinational companies have shown to play important but different roles in the development and uptake of nanotechnology in the window chain (see later on this).

5. The nano strategizing of most companies in the window chain may best be termed cautious and discreet if not secretive. As the nano hype has diminished the latter 5-7 years the attention to the risk uncertainties related to nanotech have gone up. The current case indicates that company's interests into applying nanotech is lessened or, for those already engaged in nanotech, becoming more secretive. Only companies really dedicated to nanotechnology now brand themselves with nanotechnology. The current reserved attitude means that search into nanotech opportunities are somewhat restricted particularly by early or new users and that some nanotechnological opportunities therefore will not be utilized. Also, the lacking communication on nanotech applications may backlash on the industry. Today advanced nano-coatings are standard in modern large scale glass manufacture but this is little known in the public. There are similarly other nano-applications in the window production which are little known.

6. *The eco-innovation strategizing,* in contrast, is experiencing a strong boom in the window chain and overall construction sector. All companies along the Nordic window chains show strong eco-innovation strategizing. The search for new green market opportunities is intense significantly affecting the competitive conditions and beginning to affect the roles of different companies in the chain. A result is that improvements in energy performance of windows is so considerable that windows have changed from being part of the problem to being part of the solution for achieving green energy conserving/energy plus buildings.

Hence the case exemplifies waves in the economy where nanotech seems currently to be on the down-turn (though the picture is mixed here) and eco-innovation in the up-turn. The friction to eco-innovation on the market is hereby rapidly diminishing as "green" market institutions and practices are becoming established.

The case analysis shows, however, several examples of remaining problems in market penetration of green products which illustrates a fundamental problem of many eco-innovations: It is often very complicated to estimate and communicate the environmental parameters. E.g. the environmental properties of a modern window are quite complicated, depending on a series of factors in the pane as well as in the frame, and on installation, localization and use of the window. Also economic and other benefits may only be materialized in the long term. This sets very high demands on market communication and capabilities of market actors (see also Andersen 1999, 2009a, 2009b).

7. *Eco-innovation affects nanotech development.* Clearly, eco-innovation is influencing strongly specifically on the nanotech development in the window chain. The need to outweigh possible risk issues with societal benefits in the nanotech area means that the considerable expectations of eco-innovative opportunities are very important for the industrial uptake of nanotech in the window chain. We see several examples that nanotech may offer novel green solutions to enduring problems in the window chain. We also see the rise of new problems as windows and buildings become more energy efficient/tighter such as poorer indoor climate, reduced light transmittance and increased condensation, which nanotechnology is remedying. Our studies show that fundamental nanotech properties enable several forms of smart, multifunctional solutions which have very promising eco-innovative perspectives. We have found Nordic examples that nanotechnology is already improving energy efficiency, energy control, self-cleaning glass, de-polluting materials/improving the indoor climate, environmentally friendly wood preservation and better light transmittance in glass of importance for the efficiency of solar energy and green houses. And we have seen experimentation into or a growing interest into green nanotech opportunities for .e.g. anti-condensation materials, durable paints for wood and environmentally friendly metal corrosion treatment. Many of the new niche green nano-products are of a relatively recent date and prosper from the recent greening of markets. In several cases they are experiencing a very positive commercial development which promises well for

their survival; even in the case of quite new unknown technologies such as the “Superwood” environmentally friendly wood preservation.

Generally, though there is no explicit link between “green search” and “nano search” in the window chain to day. Some of the most promising upcoming eco-innovations in the area, the new energy efficient composite window frames, are e.g. not nano-enhanced.

6. The few dominating big multinational glass manufacturers are very important technology developers in the nanotech area with their strong R&D and technical capabilities. These are well-represented in the Nordic countries through glass processing or wholesale companies, apparently because they consider the Nordic markets interesting markets for advanced glass products. They do, however, only have limited research facilities here. This complicates interaction with universities, nanotech starts-ups and window and construction companies, which is limited, e.g. when it comes to participation in green demo house developments in the Nordic countries. One of the main global glass players, the company Pilkington, has though one of their main coating plants in Sweden, which is important for (nano) technology development in Northern Europe.

7. *New entrepreneurial companies* based on specialized technological competence appear, as expected, as core nanotech developers of new niche markets. As such they are developers of some of the more radical green nano-innovations in the window chain. We have found several examples of quite innovative start-up companies; seven companies have been investigated in the three Nordic countries. With the current strong demand for green products some of these are currently experiencing a relatively easy entry into the existing window value chains, others are struggling with major barriers. Combining promises of short-term niche market entry with visions of long-term grand markets seems to be a viable approach to attract investors.

8. The role of *the intermediate, more fragmented glass-processor and window manufacturers* is more mixed when it comes to both nano- and eco-innovation. In Sweden and Finland, it seems these companies lack in-house R&D resources and risk-taking capability and are not engaged in eco-innovative nanotechnologies, but more studies are needed on this aspect. However, in Denmark, a larger window manufacturer (the Velux and Dovista companies which form part of the VKR Group), with stronger R&D capabilities show quite some absorptive capacity towards nanotechnology with fairly widespread nano capabilities. While they to some degree play an active role in actual nanotech development in the frame area, they also have nanoscientific insights into glass coatings in order to be able to select the right glass. They overall appear to form a node bringing in different nano-innovations in the window chain. We are, though not talking about nano-dedicated companies or the pursuit of very strong nano-strategies. Rather, these companies exemplify the companies which are increasingly attentive to the new nanotech opportunities and are in the process of building up more capabilities in the area. But even this level of activity is somewhat surprising given the low expectations to nano-activities in the construction sector and illustrates the beginning pervasive effect of nanotechnology.

These same companies display recently a marked shift towards more systemic and smart/active eco-innovation strategies, a trend which fits very well with the nanotechnological opportunities. Increasingly these companies take on the role as system integrators and become producers of green buildings rather than merely green windows. Hence the opportunities for nanotech uptake seem to be further reinforced with the rise of eco-innovation.

Also another somewhat smaller Danish window company (PRO TEC) is an interesting example of an incumbent company undertaken radical product and marketing innovation in pioneering the development of novel composite (energy efficient) window frames as a response to the rising green profit opportunities. Hereby they are putting pressure on the other players on the market, some of which are also on the move in this area.

9. An alternative to the scenario that component manufacturers get more involved in overall system design is that *construction companies* get involved in materials development. Based on our study we find little evidence for this. The two major application areas for glass are buildings and vehicles. While the automotive companies have venture capital subsidiaries that invest in new technologies and get involved in product development with their suppliers the large construction companies tend to be more defensive and follow a wait and see strategy.

Overall, the recent greening of the market opens a window of opportunity that not only guides the direction of search of investors but also put pressure on incumbent actors to search for new solutions and develop new capabilities, strategies and knowledge networks. Currently, it seems the greening of markets is affecting the economic organization considerably, and as yet stronger than nanotechnology is, leading to a beginning reorganization of the division of labour in the window value chains.

10. The current policy regime, mainly analyzed in the Danish case, has only partially stimulated eco-innovation in the construction sector. While regulation on energy efficiency towards buildings certainly has been a core innovation driver and let to major improvements in energy performance, it has also restricted innovation. The change towards more flexible policy measures in recent years in the construction and window area both internationally and nationally appears to be stimulating eco- innovation in new ways, particularly forwarding more systemic eco-innovations.

7.2 Policy issues and recommendations

7.2.1 Policy agendas in transition

The theme addressed in this report, green nanotech in construction, touch three policy areas; the environmental, the construction and the nano policy areas. Most of the environmental regulations towards the construction sector form part of the building regulative. Clearly, these have had a very significant direct impact on both nano and eco-innovation in the Nordic window chains. The impacts of the two other policy areas are much more indirect, and seemingly less influential for uptake of green nanotech in construction. However, it is worth noting that strategic documents on both construction and nano policy are emphasising sustainability issues as a main concern and a business opportunity to be exploited, illustrating the more horizontal role environmental issues are coming to play.

We also observe that all three policy areas are becoming more innovation oriented. We have already pointed to the significant paradigm shift in environmental policy as the market oriented eco-innovation policies increasingly come to complement the traditional regulatory approach (Andersen, 2009b). The up-coming mentioned Eco-innovation Action Plan of the EU could provide a good platform for a strengthened effort here.[62] Similarly, construction policy is paying more attention to promotion of knowledge based innovation.[63] Nanotech policy, particularly in Europe, has hitherto been very science oriented as briefly referred to in Chapter 2. There is, however, quite recently a stronger interest into developing nano-innovation policy, where the emphasis is shifting towards the industrial uptake and knowledge diffusion related to nanotech (EC, 2009a, 2009b). Among the policy instruments that are already in place in the EU, the technology platforms may be best suited for the promotion of nano-innovation. The platforms bring together varies stakeholders to investigate and develop current and future opportunities. These technology platforms are, however, mainly oriented towards quite high tech application areas (the European Nanoelectronics Initiative, Photonics21 ETP, Nanomedicine ETP, Sustainable Chemistry) and less towards more traditional industries (EC, 2009a). However, in 2006, Germany launched a national nano strategy oriented towards industrial uptake in particular sectors, which included a strategy for nano-enabled construction

[62] Non- paper: “Innovation for a Sustainable Future: From the Environmental Technologies Action Plan to the EU Eco-innovation Action Plan”, presented at the Stakeholder Consultation Meeting on the EU Eco-innovation Action Plan, February 11, 2010.

[63] Source: http://www.ectp.org/documentation/ECTP-SRA-2005_12_23.pdf

started in 2007. The strategy has a green focus.[64]. Our recommendations seek to relate to the above new policy trends.

7.2.2 Policy recommendations

The theme of green nanotech in construction is an area strongly influenced by policy making, the nanotech area mainly via public funding of nanoscience, the environmental area mainly via normative regulation, the construction area more mixed. We have identified some limitations in current policymaking, but it is also clear that interesting new trends are under way both nationally and internationally (EU). Our recommendations seek to feed into and support the new trends towards a greater innovation oriented approach to nano, construction and environmental policy. The recommendations fall at several levels; from the more principle ones to specific suggestions for concrete measures.

1. Our first point is the need to develop *more coordinated policy measures* for a stronger innovation oriented policy approach to succeed. For companies no policies function alone but always in combination. Looking into how different policies may restrict or enhance each other is needed. Our analyses in the window area have demonstrated that to materialise the potential synergies between nanotech and green construction, there is a need to combine regulatory and innovation supporting policies.

2. Eco-innovation is becoming the perhaps most important driver for innovation in construction. Despite many years of environmental initiatives in the construction area in the Nordic countries, the room for technological improvement is still considerable. Hitherto, many green building technologies have emerged from green grass root initiatives and have little science based. Hence there is a great need to look into more high-tech solutions for green buildings and cities. Particularly the tendencies towards more systemic solutions for smart high tech green buildings are novel in this fragmented sector and may possess the greatest commercial potential. Currently, national initiatives for advanced green demo-houses are advancing the more radical eco-innovations in the window and construction area. *A Nordic eco-innovation strategy with a global outlook for the development and exportation of green buildings* could push the development of advanced (nanotech based) eco-innovations in the Nordic countries. An expanding knowledge base in green nanotech for construction could be consolidated further at the Nordic level e.g. through common R&D programs, teaching and research mobility schemes and sharing of instrumentation and equipment.
3. While we have identified quite a number of applications of green nanotech in the window chain, still the overall amount of commercial nano activity is limited. There is an unexploited potential in areas where there is a lot of nanoscientific activity in The Nordic countries that is not yet translated into commercial activity. While we recognize that policy needs to be long sighted as gestation times are long for new technologies, we believe that there is room for improvement in making nano policies more problem and innovation oriented. We suggest that *selection criteria for public funding of nano projects should be reconsidered* and that commercial appraisal systems are strengthened to stimulate a greater industrial uptake (this might be particularly relevant in Denmark and Sweden while Finland already has quite a strong focus on this). One could also consider including environmental criteria to promote the development of green nanotech more systematically. To quote the CEO of the Danish nanodedicated company Photocat, after having read our analysis: “Had it been my tax money which had been invested into this nano area, I had to say the result is very unsatisfactory. Hardly anything

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[64] See the German call: http://www.bmbf.de/foerderungen/10471.php. for the strategy "*Nanotechnology in the Construction Industry – NanoTecture: Exploration of potentials for increased resource- and energy-reduction, and novel functionalities"*. The Strategy is based on the *Materials Innovations for Industry and Society – WING*, as well as the Nano-Initiative Action Plan 2010, from November 2006.

has come out of ten years of hard work with lots of nano science projects at the universities". Michael Humle, CEO of Photocat, February 16, 2010.

4. There is a strong need for policy measures targeted at *the uptake of nanotechnology at the sectoral/industry level*. Our analysis indicates the need to consider the specific conditions for nanotech uptake in given sectors. Nano capabilities, links to universities, risk aversion ect. matters for the absorptive capacity. *Nordic strategies aimed at given sectors for nanotech uptake in all the Nordic countries* could create a considerable momentum and forum for exchange of best practices and experiences learned. Sector specific teaching schemes could form part of this improving the nano knowledge base in none the least the traditional sectors.

5. There is a need to *promote nano-dedicated green start-ups* to boost green nano-innovation as these are important particularly for the more radical green nanotech development. One promising avenue is to link up start-ups to incumbents early on. In Finland, this has been the strategy of the FinNano program. However, there are challenges in connecting traditional industries with emerging nanotech due to cognitive barriers and the potential need for radically new production processes and business models.

6. There is a need to create *bridging arenas which could close the cognitive and institutional gap between nanoscience and industrial application areas, such as construction*. Such arenas could e.g. consist of matchmaking and mobilization initiatives, demonstrations, combined research and innovation programmes and conferences and dissemination activities. This could guide nano scientists and nano companies towards industrial and societal problems and incumbent firms towards new nano-enabled solutions. These arenas could be national or formed at the Nordic level. The Nordic level could be important since the stock of nano-dedicated companies in each country is limited. The EU funded project "Nano Connects Scandinavia" (2009-2012) is a fairly big (34 mio. DKK) project with a broad focus on supporting education, research and innovation in nanotechnology in southwest Scandinavia. While being geographically limited and perhaps having a too wide focus, the activities undertaken could serve as inspiration for wider Nordic collaborative actions in this area.

7. Our study has also highlighted the need for *policy initiatives directed at the value chain dynamics.* Policies should seek to identify and create incentives for the different kinds of companies involved in a given innovation along the chain. Particularly in areas of emergence, (relevant for nanotechnology as well as the green market), the uncertainties and transaction costs are so considerable that there is a need to support coordinated or cluster oriented measures. E.g. the EU "lead market initiative" could prove valid for exploiting the "green-nano-construction" area. It is necessary to identify the bottlenecks in the chain and to create continuous incentives both for the leaders and the laggards towards eco-innovation and nano-innovation. Specifically, we have identified the absence of progressive industrialists in window and construction manufacture who could up-scale nanotech and provide avenues for large scale commercialization in the construction sector.

8. We see a need for *increased demand-side policies to support eco-innovation as well as nano-innovation.* Both areas are very complex and associated with high uncertainties and the benefits are difficult to communicate on the market. The window case is a very good example of how difficult it is to communicate the many properties, none the least the green ones, of modern advanced windows to users; particularly to consumers with little insight into environmental issues and nanotechnology. Clearly *public green procurement schemes* in the Nordic countries have been inadequate in the window area (and generally towards green construction) and much more stringent activities ought to take place to boost the green market. There is also a need for the advancement of *advanced internet based green marketing tools and campaigns*. And finally, in the longer time perspective, there is a need to raise the knowledge level on product related environmental issues via education schemes at all levels in society.

9. Related to this, there is a need – not only for risk assessments of new materials in general – but also for *initiatives to help companies assess and handle possible environmental, health and safety (EHS) risks* related to nanotech. Clearly, risk issues are a major barrier for the commercialization of nanotech in the construction area, and companies have developed insufficient strategies and capabilities to deal with this. The cautious or secretive strategy of many companies

10. Finally, there is a need for *strategic support to develop more innovation oriented nano policies and eco-innovation policies at national and Nordic levels. S*ome initiatives are taken at the EU level, e.g. the EU "NanoObservatory" scheme running right now doing a first crude monitoring of market trends and nano opportunities in different sectors. But these do not suffice as policy guidance. We need more in depth analysis into the industrial dynamics of nanotechnology and eco-innovation as it takes place in different sectors. We need e.g. to know more about the absorptive capacities of different sectors towards nanotechnology. And we need to know more about the sectoral specificities in eco-innovative behaviour. We also need to investigate in depth the "greenness" of the Nordic countries as opposed to other countries and regions. There is much myth about this but little substantial knowledge, i.e. who are the green leaders and the green laggards internationally. This is necessary to identify Nordic strongholds and potentialities to nurture further, see also research needs below.

7.3 Future research needs

Both eco-innovation and innovation in nanotech and construction are big themes and adding them together opens up for a very big research agenda, most of which have been little studied so far from an innovation economic perspective. This study has only managed a first look into the trends and dynamics in green nanotech in construction, so future research needs are many. Interesting research projects could be:

- Analyses into green nano trends and dynamics in the Nordic countries of other traditional (or "low tech") industries with potential for 'green renewal/growth', to elaborate on whether similar issues arise there.

- Investigate the (nano and eco-) innovation dynamics of the window chain as opposed to other segments of the construction industry in the Nordic countries. Is the window segment more green or more nano than the rest of the sector, where and why?

- More detailed analysis into the window chain dynamics, particularly the downstream end, looking into the role of the incumbent construction companies towards eco-innovative and nanotech component solutions.

- An analysis into the eco-innovative capacity of the Nordic countries as opposed to other countries in the construction sector. I.e. to what degree and in which construction fields are the Nordic countries in the lead, where are we laggards, and why?

- An analysis into the greening of the Nordic innovation systems, at the national level and/or the sectoral level (e.g. the construction sector). I.e. a longitudinal study of the co-evolutionary processes involved in the transformation of innovation systems. Rather than a benchmark study this is an analysis of the innovation system dynamics involved over time which is so far little analyzed.

- An analysis into the Nordic position in the global greening of the economy. How do we position ourselves internationally with changes in the international division of eco-innovative labour? How do we respond to the rapid high-tech greening of the Asian countries?

  - A policy regime analysis positioning Nordic eco-innovation policies in an international context, looking specifically into possible Nordic characteristics and similarities over time, compared to international trends in policy development.

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